Citation:

Orifici, A 2014, 'Control of composite material crack branching for improved fracture toughness', in S. Chernyshev (ed.) Proceedings of the 29th Congress of the International Council of the Aeronautical Sciences (ICAS 2014), Germany, 7 - 12 September 2014, pp. 1-8.

29th Congress of the International Council
of the Aeronautical Sciences
St. Petersburg, Russia; September 7-12, 2014

CONTROL OF COMPOSITE MATERIAL CRACK BRANCHING FOR IMPROVED FRACTURE TOUGHNESS

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Abstract

An experimental investigation was conducted to develop techniques for controlling crack branching in composite laminates. Double cantilever beam specimens were tested to study mode I dominated crack growth. Embedded flaws were generated using ply gaps and strips of non-stick film, both individually and in combination as a "branch flaw". Crack branching in 0° plies was generated in an inconsistent manner using ply gaps, but in a consistent manner using branch flaws. Branching through 90° plies occurred automatically due to their orientation, and could be further controlled using embedded delamination flaws. Crack branching in 45° plies was more complex, but could be controlled using ply gaps as well as branch flaws. These discoveries were combined to demonstrate crack branch control through a quasi-isotropic laminate. The results have application to design of future high toughness and damage tolerant aerospace composites.

1 Introduction

In natural materials such as bone and wood, crack bifurcation and deflection (branching) are well-known mechanisms that promote increased fracture toughness [1]. In contrast, laminated composite materials such as those increasingly used on aircraft structures typically show rapid and catastrophic crack growth along a single crack plane between plies. Laminated composites can show high toughness phenomena, which include crack branching, where a crack migrates from one plane to another, and fibre bridging, where fibres remain attached across the crack plane [2]. However, these high toughness phenomena are not exploited as part of the design of composite structures, and are often treated as random occurrences or unwanted by-products of crack growth.

As such, in the aerospace industry composite materials are typically designed for a "no growth" scenario where catastrophic failure is assumed. This is because there is a lack of understanding on how crack growth can be controlled such that these mechanisms are promoted in a reliable manner. Despite this, the potential exists to exploit the high toughness potential of composite laminates through the improved control of crack branching. This can lead to a future design scenario where crack growth is allowed under safe operating conditions due to the promotion of stable high toughness crack growth. Such a concept requires knowledge of crack branching mechanisms and the effectiveness of crack control concepts in different loading scenarios and laminate configurations.

In this work an experimental investigation is conducted to study the occurrence of these high toughness mechanisms, and focus on ways they can be repeatedly promoted across a range of different laminate configurations. The goal of this study is to discover methods to control crack growth such that high toughness crack growth is seen in a repeatable manner. The investigation focuses on the use of embedded flaws in the potential crack path (behind the crack tip) that can act to influence and direct the crack growth.

2 Specimen definition

The experimental analysis in this work focused on mode I interlaminar crack growth using the Double Cantilever Beam (DCB) specimen, according to the ISO Standard [3]. The specimen design is a uni-directional laminate with a mid-plane pre-crack on one end that is loaded in mode I opening to force the crack to propagate along the mid-plane. This specimen was modified to investigate different laminate combinations, and different embedded flaws. The nominal specimen geometry is shown in Fig. 1. Variations in ply angles considered only the angles of typical aerospace quasi-isotropic laminates, that is, 0°, ±45° and 90°. All specimens used unidirectional carbon/epoxy VTM-264 prepreg composite plies, with nominal ply thickness 0.22 mm. Pre-cracks in the laminate were created using strips of ethylene-tetrafluoroethylene (ETFE) that were included between plies during the layup process. For example, EFTE strips embedded between plies generated a “delamination flaw”, such as the one used at the edge of the specimen to create the initial starter crack. Delamination flaws embedded within the specimen (away from the specimen edge) were typically 10 mm in length, though lengths of 20 mm were also investigated. Spacing between successive flaws was typically 10 mm. At least five specimens were tested for each configuration.

Experimental results are presented as a schematic illustrating the typical crack growth pattern, the fracture toughness values taken at the initiation of crack growth (G_{init}) and averaged over the entire crack growth (G_{avg}), and a representative graph of the applied load (P) versus applied displacement ($\delta/2$). The fracture toughness values are provided with the coefficient of variation (standard deviation divided by average) in parentheses. Fracture toughness values all have units of J/m^2. Crack growth schematics are always shown with the initial crack at the left specimen edge and crack growth from left to right.

One complexity in the interpretation of results from DCB specimens is the occurrence of fibre bridging, where fibres remain connected across the crack face and increase the fracture toughness of the specimen. The occurrence of fibre bridging makes characterisation of fracture toughness more complex, as the degree of fibre bridging is dependent on many factors and difficult to isolate for a given specimen. As such, the results related to fracture toughness need to be interpreted with this in mind, and the focus of the investigation remains on developing crack control concepts for composite laminates.

3 Experimental results

A wide range of specimen configurations were investigated, covering variations in laminate and embedded flaw type and arrangement. These results are summarised in the sections below, which are grouped according to the crack branch outcome. These crack branch outcomes are the understanding on the method for controlling crack branching through a particular ply orientation or laminate.

3.1 Crack branch through a 0° ply

The standard uni-directional laminate DCB specimen has the crack growth direction aligned with the fibres, so that the crack is at a [0°/0°] interface and bounded by 0° plies on either side. Crack branching in this situation would require fracture of fibres in one of the bounding 0° plies. As the energy to break the interlaminar bond between the plies is much less than the energy for fibre fracture, the crack remains within its original location as it propagates along the specimen length. This is shown in Fig. 2(a).

To generate a branch through a 0° ply it is clear that some break in the continuous 0° ply is needed. Specimens were investigated with a so-called “ply gap” or “ply cut”, which is a discontinuity in the ply. These were created by laying the ply down in two parts, with a small (1 mm) gap that fills with resin during curing. Results are summarised in Fig. 2(b). The use of ply gaps was found to be able to generate crack branching through a 0° ply. However, there were two key aspects of this behaviour. The first is that the resin-rich zone that exists in the ply gap is actually a region of increased toughness. As such, when the crack reached this region, crack growth was delayed and the load increased until fracture through the resin could occur. The second aspect was that the crack did not always branch through a ply gap region. Furthermore, specimens with a series of ply gaps in a unidirectional laminate showed that once a crack branched through a ply gap, it would not return to the original interface if it passed through another ply gap region. Both of these aspects make the use of ply gaps for control of crack branching through 0° plies unsuitable, as they demonstrate a lack of consistency and lack of control of the crack path.

To overcome the unsuitable nature of ply gaps for crack branching through 0° plies, a new type of crack branch flaw was investigated. This was created by laying one part of the ply down, placing an ETFE strip in the ply gap region, then laying the second part of the ply down to complete the ply. This created a flaw that combined a ply gap with a pre-existing crack that traversed the ply gap region. The results are summarised in Fig. 2(c), and a sample crack pattern as observed from the specimen edge is shown in Fig. 3(a). The use of this "branch flaw" was shown to be highly effective in generating a crack branch, in a consistent and controllable manner. However, crack branching through a branch flaw was also associated with large drops in load and low fracture toughness.

3.2 Crack branch through a 90° ply

Crack branching through 90° plies was investigated by using laminates with 0° and 90° plies, where the initial crack was located within a [0°/90°] interface. For these specimens, crack branching was found to occur immediately upon the initiation of crack growth. This is expected as in 90° plies the fibres are transverse and perpendicular to the proposed crack growth direction, and as such present an easy path for crack branching through only matrix material. The crack branching angle varied from 60° to 90°, with reference to the initial interface. For some specimens, cracks that branched from the initial interface to the other side of the 90° ply subsequently saw crack branching back to the original interface, such that a continual zig-zag pattern was observed. However, this was not consistent, and it was more common for a crack to continue along the same interface once it had initially branched away from the initial interface. This is shown in Fig. 4(a). A consistent zig-zag pattern was generated for crack branching through two 90° plies, with crack propagation segments of approximately 0.92 mm connected by crack branches at around 45° through the ply. This is shown in Fig. 4(b) and in Fig. 3(b).

Specimens were investigated with a sequence of embedded ETFE strips that were spaced along an initial [0°/90°] interface. The results of these are summarised in Fig. 4(c). These specimens showed that a delamination flaw was able to consistently attract the crack back to the initial interface. This demonstrates a further crack control technique for crack branching through 90° plies.

3.2 Crack branch through a 45° ply

Crack branching through 90° plies was investigated by using laminates with 0° and 90° Similar to the situation for 90° plies, for an initial crack at a [0°/45°] interface, crack branching was seen to occur immediately upon initiation of crack growth. However, instead of a simple vertical crack, a more complex crack pattern was observed. Firstly, the crack often took a more torturous path through the middle of the 45° ply, and multiple crack paths were seen. This was reflected in increased fracture toughness in propagation, seen in higher G_{avg} values. Further, the crack branching occurred at 45° across the width of the specimen, that is, in plan view the line of crack branching was at 45° to the initially straight crack front. This meant that on one side of the specimen (the "front" as viewed with the initial crack on the left) crack branching was seen from the edge of the initial crack, whilst on the other side of the specimen (the "back") the crack propagated along the initial interface until it reached a point where it intersected with 45° fibres that started on the other edge. This is shown in Fig. 5(a), where both front and back side crack paths are shown, and the progression of the crack front from straight to at a 45° angle is reflected in a change in slope in the load-displacement results.

Crack growth from a [45°/45°] interface did not show clear or consistent crack branching behaviour, as shown in Fig. 4(b). For this case, the crack grew within the 45° plies and also sometimes along an adjacent [45°/0°] interface, with multiple crack paths. This is shown in Fig. 5(b).

Crack branching through 45° plies was not shown to be influenced by delamination flaws along the initial interface, in the same way as for 90° plies shown in Fig. 4(c). Crack growth with this flaw configuration for a [0°/45°] interface did show rapid crack growth associated with the region of the delamination flaw, but the crack did not return to the original interface. However, the use of a ply gap for a 0° ply on the other side of a 45° ply was found to consistently cause crack branching through the 45° ply. This is shown in Fig. 5(c), and demonstrates that crack branching through 45° plies could be controlled by the stress concentration around the ply gap region caused by the termination of 0° plies. For this to occur in a consistent manner, there needed to be sufficient spacing between the initial crack and the ply gap to allow for crack branching across the width of the specimen. Crack branching was separately able to be demonstrated in a consistent manner through a 45° ply using the branch flaw concept shown for 0° plies in Fig. 4(c), though as seen for the 0° plies this resulted in a large drop in load as the crack passed through the branch flaw.

3.2 Crack branch through a quasi-isotropic laminate

A typical aerospace quasi-isotropic laminate was investigated to demonstrate that the combination of crack growth outcomes of the previous sections could be used to control crack branching through a multi-directional laminate. A $[45,0,-45,90]_{2S}$ laminate was used, with delamination flaws to attract branching through 90° plies, branch flaws to cause branching through 0° plies and also to attract branching through 45° plies, and sufficient spacing to ensure branching across the width of the ±45° plies. The results are shown in Fig. 6, where the crack was intended to be deflected (branched) away from the initial interface at every instance. These specimens saw crack growth along the intended crack path for all instances, which confirms the single ply outcomes identified previously.

4 Conclusion

An experimental investigation was conducted to discover methods for controlling crack branching in composite laminates. Crack branching through 0° plies could be caused by using a ply gap region, though the resin rich zone affected the repeatability of results. A crack branch flaw was proposed that combined a ply gap with a pre-existing branch flaw, and was shown to be highly effective in controlling crack branching through 0° plies. Crack branching through 90° plies occurred immediately upon crack growth, but could also be controlled with a delamination flaw. Crack branching through 45° plies occurred immediately, but was more complex as multiple cracks were seen along a more torturous path that involved crack branching at 45° across the specimen width. However, crack branching through 45° plies was able to be controlled through both ply gaps and branch flaws. The combination of all of these outcomes was applied to demonstrate crack branch control through a quasi-isotropic laminate. The results have application to the use of crack control for future high toughness and damage tolerant composite laminates.

Acknowledgments

The author would like to thank Mr Robert Ryan and Mr Peter Tkatchyk of RMIT University for technical support in manufacture and testing, and Phisit Wongwichit and Nuth Wiwatanawongsa of RMIT University for their assistance with specimen design, manufacture and testing.

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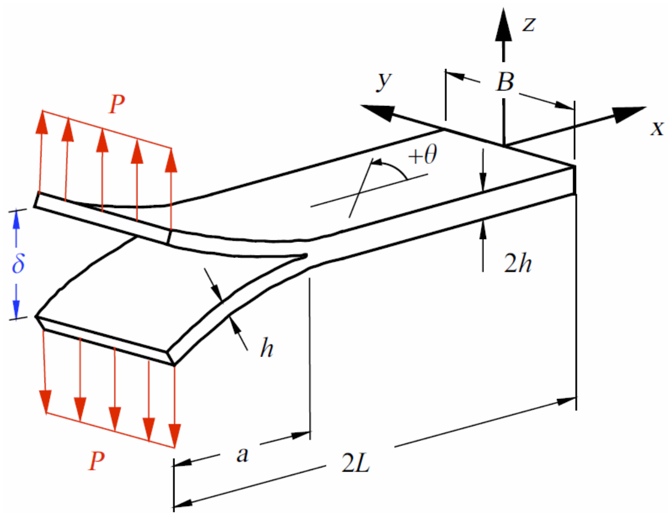


B	20 mm
$2h$	3 mm
$2L$	130 mm
a	50 mm

Fig. 1. DCB baseline specimen dimensions.

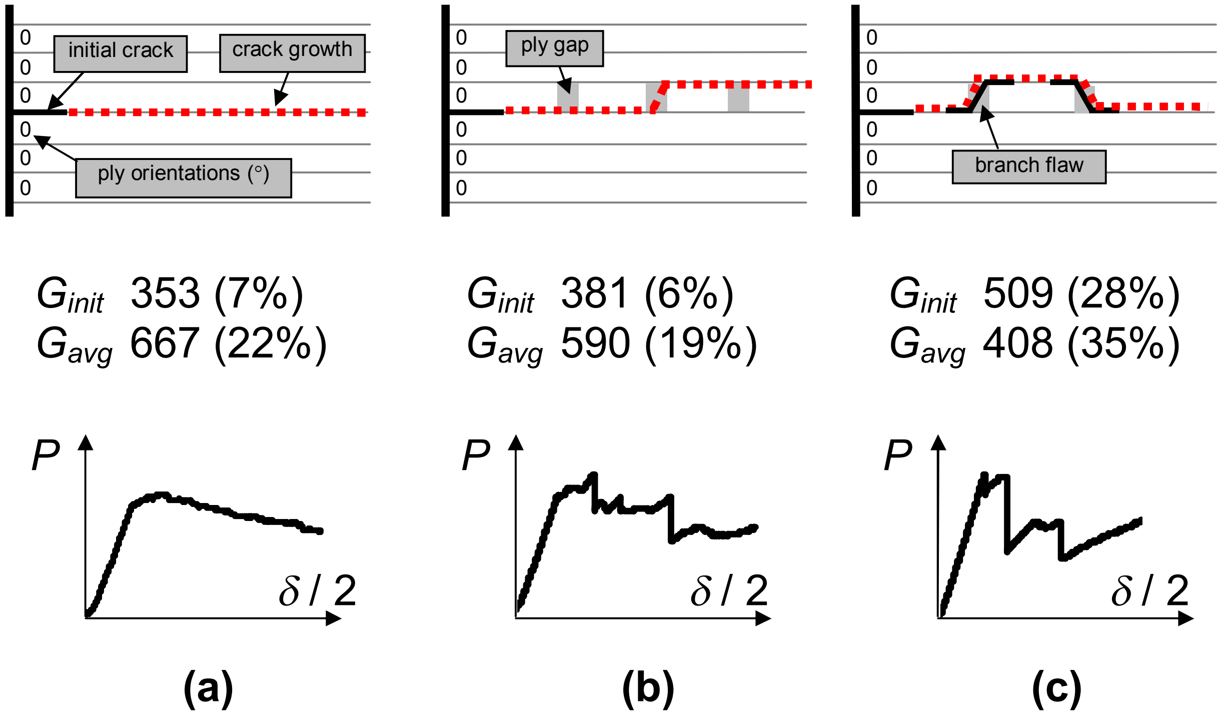


Fig. 2. Crack growth results investigating branching through a 0° ply.

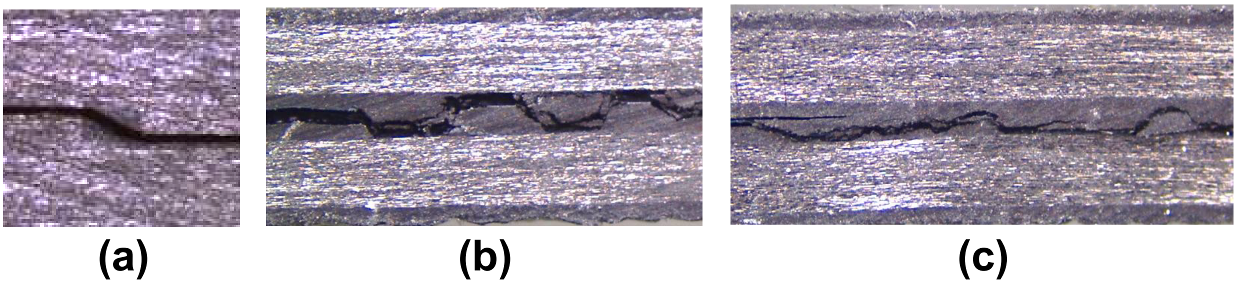


Fig. 3. Crack growth patterns. (a) Branch flaw through 0° plies. (b) Zig-zag pattern through two 90° plies. (c) Multiple paths in two 45° plies.

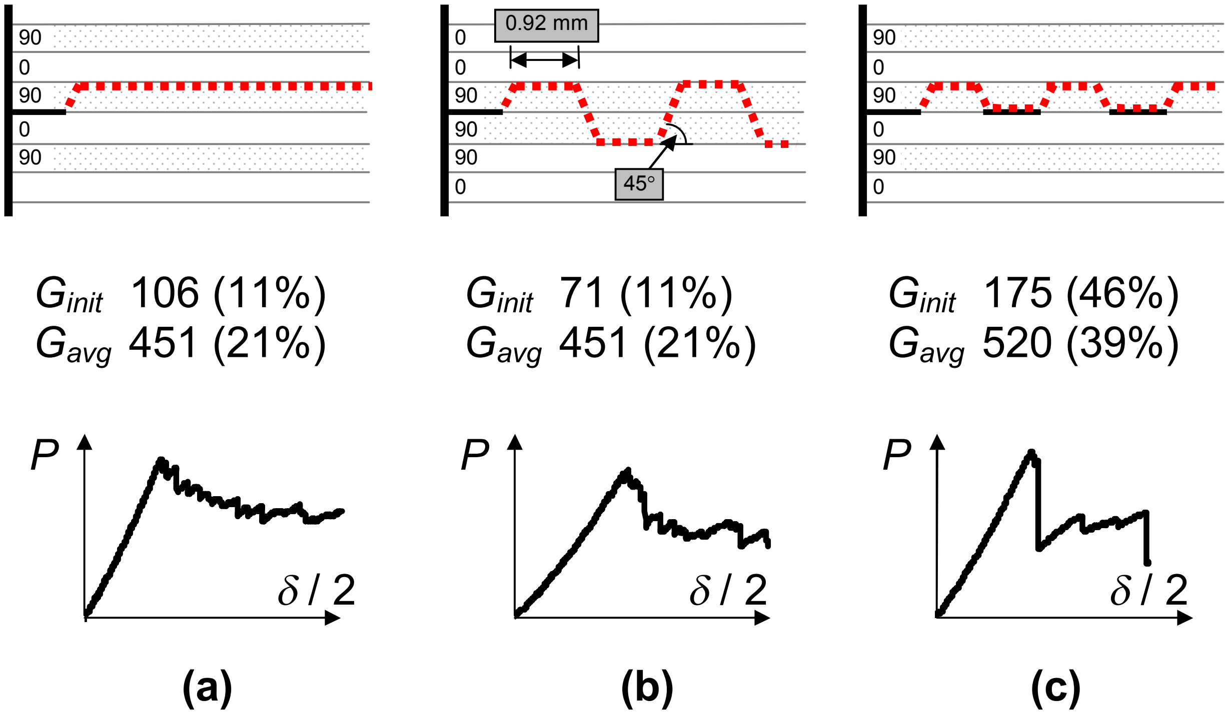
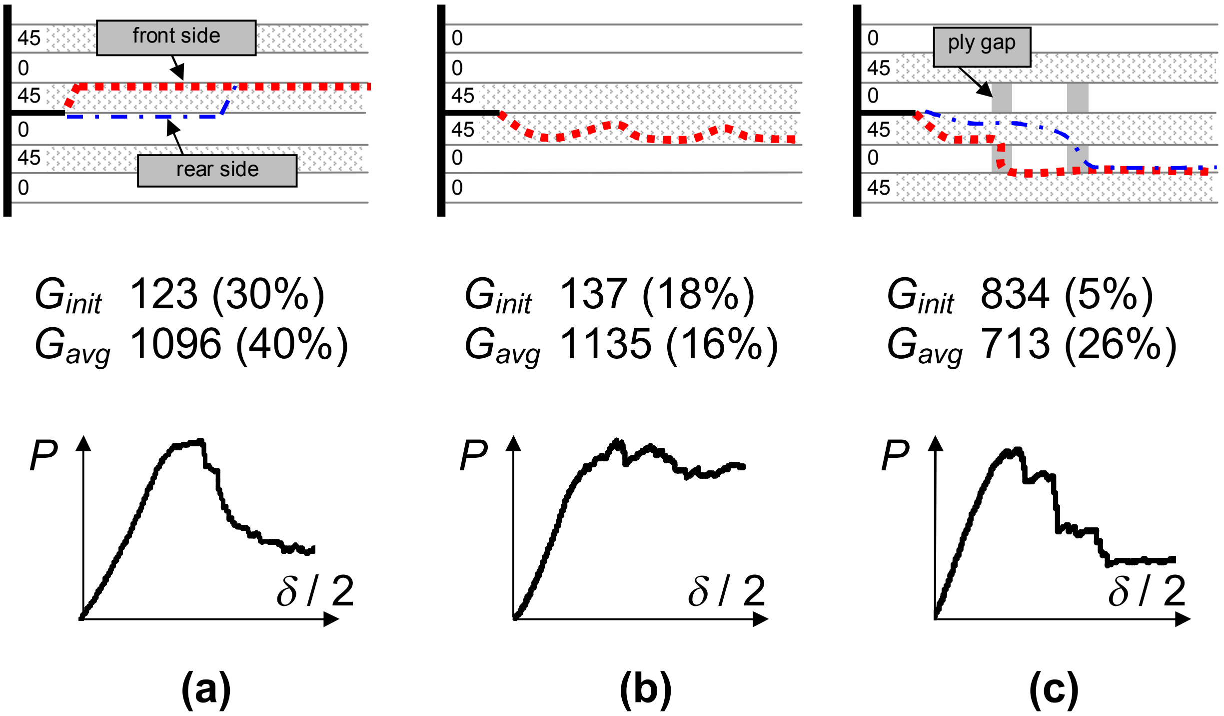


Fig. 4. Crack growth results investigating branching through a 90° ply.



(a) (b) (c)

Fig. 5. **Crack growth results investigating branching through a 45° ply.**

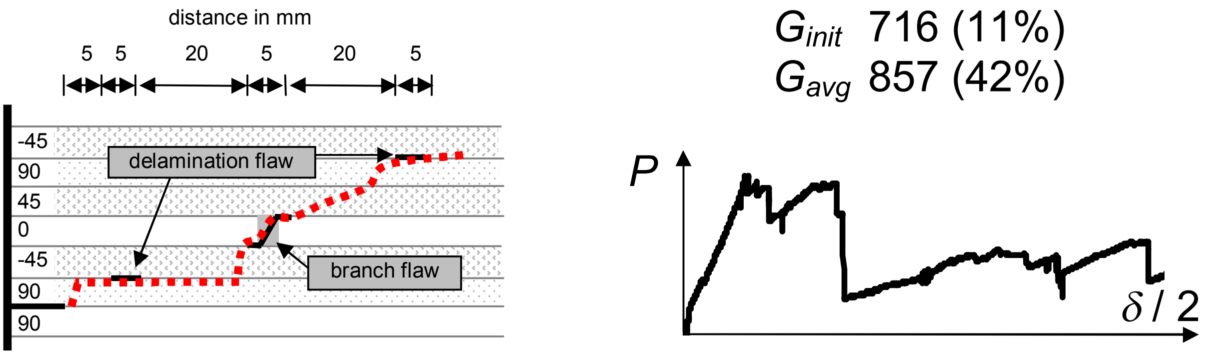


Fig. 6. **Crack growth results investigating branching through a quasi-isotropic laminate.**