A review on mode-I interlaminar fracture toughness of fibre reinforced composites

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Abstract. Composite material has been growing rapidly throughout the year for its unique properties in comparisons with metal. Recently, there has been a growth on studying the way to reduce the delamination failure, which is the primary challenge on laminated fibre composite. This failure can degrade the strength of composite materials, hence loses its function. In this review, database search was performed using the keywords search on “interlaminar fracture toughness”, “double cantilever beam”, “delamination resistance” and “Mode-I $G_{IC}$”. The searches were performed on Google Scholar, Scopus and Web of Science with further cross-referencing with other databases. Most relevant studies were selected for review and referencing by the author. This review paper gives a brief explanation on Mode-I interlaminar fracture toughness of composite material. This fracture mode is the most common modes on studying the delamination failure.

1. Introduction
By definition, composite material is a material comprises of two or more material; reinforcing agent (fibre, particles or sheets) and the matrix phase (polymers, metals or ceramics) [1-2]. Composite materials are also introduced with the aim to enhance the properties of the material that is being bonded together; matrix and reinforcement. The matrix functions as a support for the reinforcement, whereas; the reinforcement provides unique mechanical and physical properties that improve the matrix properties. The application of composite material has been growing rapidly in the field of automobile, aerospace, marine, nuclear, biomedical and other engineering field. For example, there is about 30% of the external surface of the Boeing 767 consists of composite material [3]. Moreover, in 2000, polyurethane reinforced with a mixed of flax/sisal material door trim panels were introduced by Audi during the launched of its A2 midrange car [4]. According to the market research published by Lucintel on 2016, the global market is expected to reach an estimated of $37.3 billion by 2021 and rise at a CAGR (Compound Annual Growth Rate) of 5.1% from 2016 to 2021 [5].

Nowadays, fibre reinforced polymer composite (FRP) is the most commonly used among other composite materials due to its unique properties; high specific strength and lightweight. However, FRP is unable to resist defect initiation and propagation when compared to metals [6]. These laminated fibre composites are most likely to form delamination damage. The characterization of the delamination resistance has gained a lot of interest among researchers. The Mode-I double cantilever beam (DCB) theory is commonly used for studying the delamination resistance [7-8]. In the DCB testing, a resistance-type fracture develops as the delamination grows from the insert. In the beginning
of the delamination growth, the calculated $G_{IC}$ will increase monotonically, and subsequently stabilize as the delamination growth. The reason to observe the resistance during delamination is due to the development of fibre bridging [9].

2. Interlaminar Fracture Toughness

Interlaminar fracture or delamination damage is the primary challenge for the laminated fibre composite. This is because these factors can degrade the strength of the laminate and subsequently leads to failure. The primary factors which affect the fracture of FRP composites are speed of loading, stress concentration, temperature, and thermal shock [10]. It is also known that the woven fabric composites provide more damage tolerant in comparisons to unwoven fabrics. This is because of the non-planar interply structure of woven-fabric composites, the interaction between the delamination crack, the matrix regions and the weave structure during propagation, will result in crack growth [11].

The interlaminar performance are characterized by their weakness towards the sheer stress and tensile stress [12]. According to Zulkifli R et al. [1], when the number of layers increases, the stiffness and interlaminar fracture toughness also found to be increasing. Hence, if the material has a high capability to dissipate elastic energy without a catastrophic failure during the crack propagation, the fracture toughness of the material is high.

Interlaminar fracture comprises energy losses in term of matrix cracking, fibre breakage, fibre pull-out, fibre slipping and fibre de-bonding, which differ from metals where fracture toughness depends on the energy dissipates at the crack tip [14]. There are three modes of fracture by which a load can operate a crack, that is, Mode-I (tensile), Mode-II (shear), Mode-III (tearing shear), or by the combination of these Modes as shown in figure 1 [15], [16]. Delamination damage, which is the most predominant problem caused, can be study using these fracture mechanics approach with the critical strain energy as a standard [1].

![Fracture Modes](image)

**Figure 1. Fracture Modes** [16]

Delamination damage is the result from low velocity impact caused by interlaminar shear stress and occur when the interlaminar stress exceed the interlaminar strength level. Interlaminar stress is caused by the geometry and the loading parameter, while the interlaminar strength depends on the material properties. Hence, to achieve the optimum delamination resistance, it is necessary to match the optimum parameter to achieve the low interlaminar stress level with high interlaminar strength level. Delamination resistance is increased when there is a decreasing of mismatch between the lamina, while there is a possibility of debonding decreasing with the decreasing mismatch between the material constituents. The difference between debonding and delamination is that debonding occurs when two materials stop adhering to each other. On the contrary, delamination is a failure of laminated material, which leads to separation of the plies. When a composite material has a large difference in fibre and the matrix stiffness, the mismatching coefficient will also be higher [13]. For example,
carbon/epoxy composites have a higher mismatching coefficient compare to jute/epoxy, thus larger delamination area is expected to occur.

3. Mode-I Double Cantilever Beam Testing

The Mode-I testing follows the standard specimen of ASTM D5528-13 to measure the Mode-I fracture toughness, $G_{IC}$, of continuous fibre reinforced composite material. The specimens used in this testing are the double cantilever beam (DCB) specimen, figure 2.

![Double Cantilever Beam Specimen](image)

Figure 2. Double Cantilever Beam Specimen [1]

The position for delamination opening should be inserted between the plies using a non-adhesive film which approximately 13 $\mu$m thickness, and the length of the film is 50 mm, plus the extra length of the hinges. The length of the specimen should be at least 125 mm and 20 to 25 mm wide. The specimen used a constant crosshead rate between 1 to 5 mm/min to promote delamination. Delamination lengths are determined visually, but for more accurate readings, a travelling microscope is recommended.

The calculation for the analysis of the $G_{IC}$ can be made through three different theories; namely the modified beam theory (MBT), a compliance calibration method (CC) and a modified compliance calibration method (MCC), as given in the equation respectively [9], [17]. It has been reported that each is being differ not more than 3.1%. However, MBT data reduction method yields the most conservative value of $G_{IC}$ for 80% of the specimen tested and are the most recommended data reduction method [18].

- Modified Beam Theory (MBT)

$$G_I = \frac{3P\delta}{2b(a+\Delta)}$$  \hspace{1cm} (1)

where, $P$ is the load applied and $\delta$ is the load point displacement. Whereas, $b$ specimen width and $a$ is the delamination length. While lastly, $\Delta$ is the correction for the delamination length. The way of correcting this theory is by treating the DCB as if it has a slightly longer delamination, $(a + \Delta)$, as the $\Delta$ can be determined experimentally by generate at least a square plot of the cube root of the $C^{\frac{1}{3}}$ as shown in the graph in figure 3 (a) [9]. $C$ is the ratio of the load point displacement to the applied load, $\frac{\delta}{P}$.
• Compliance Calibration (CC)
\[ G_I = \frac{nP\delta}{2ba} \]  

where, \( n \) is the exponent from the straight line drawn on the graph result. The value of \( n \) can be calculated when \( \frac{\Delta y}{\Delta x} \), where \( \Delta y \) and \( \Delta x \) can be defined as shown in the graph below; figure 3 (b) [9].

• Modified Compliance Calibration (MCC)
\[ G_I = \frac{3P^2C^{2/3}}{2A_1bh} \]  

where, \( h \) is the thickness of the specimen, \( A_1 \) is the slope of the line which generate a least square plot of the delamination length by specimen thickness, \( \frac{a}{h} \), as a function of the cube root compliance as shown in figure 3 (c) [9].

As reported by F.A. Almansour et al. [17], the MBT gives the lowest and more conservative value for both initiation and propagation toughness for all specimens as depicted in Figure 4. Furthermore, the \( G_{ic} \) for a wet sample is low compared to dry because of the high moisture absorption by the flax fibre, which leads to a weak fibre matrix interface. Moreover, the presence of water can create surface degradation and eventually cause micro-cracking, reduce in the fracture toughness and de-bonding in the composites. The fracture mechanics showed energy dissipation through matrix deformation, fibre de-bonding, fibre breakage and fibre pull-out. Furthermore, a high stress concentration around stitch fibres can also reduce the fracture toughness. This is because a higher amount stitched fibres can cause an in-plane fibre misalignment [17, 19].

Figure 3. Graph of Fracture Modes Theory, (a) Modified Beam Theory, (b) Compliance Calibration and (c) Modified Compliance Calibration
Figure 4. Graph of initiation $G_{IC}$ and propagation $G_{IC}$ against wet and dry flax fibre[17]

According to Zulkifli R et al., the number of layers of fibre gives high impact on the interlaminar fracture toughness. Hence, this results in the increase of stiffness of the fibre and as well as the interlaminar fracture toughness of the composites. When the interlaminar fracture toughness increases, the delamination damage grows slowly and stable. Besides, the propagation values away from the crack initiation were higher than the initiation values. The toughness of the initiation values is required. This is because most woven DCB specimens, fibre bridging occurs as the delamination progress further [1].

According to P. Suppakul and S. Bandyopadhyay [11], the mode-I of strain energy release rate ($G_{I}$) were generated to determine the initiation and propagation of delamination on a specimen. The twill weave shows the highest $G_{IC}$ value, while 8 harness satin weave gives the highest value of $G_{II}$ value. However, there is a greater number of fractured fibre occurred on the twill weave laminates compared to that of the plain weave even though the plain weave gives the lowest value for both the $G_{IC}$ value and the $G_{II}$ value. Fibre bridging is one of the mechanism which contributing to the fracture resistance on the twill weave, quadrant 4-harness satin weave and 8-harness satin weave laminates, even though twill weave has the highest values of fracture energies. Nevertheless, there is no indication of fibre bridging occur on the plain weave glass/vinyl ester laminate, due to its lowest values of fracture energies. This effect is associated with the overall weave pattern and the relative contribution of the individual microdamage on the interface [20].

Moreover, as reported by M. Pinto et al. [21], a woven fabrics showed 28% greater initiation toughness than the unidirectional because of the fibre bridging and increased in the interaction of the intra-ply. The author also stated that a plain wave experienced a high degree of nesting, which subsequently exhibited more interaction between the laminates. M. Ravandi et al. [22] also stated that the $G_{IC}$ values for unidirectional glass fibre composite shown to be less than the unidirectional flax fibre, which is due to the large difference in the bridging across the delamination plane. However, the $G_{IC}$ values for woven flax fibre shows three times higher than the unidirectional flax fibre.

The difference between flax fibre and glass fibre is that the flax fibre possesses superior mechanical properties such as low tensile properties and elongation at break but the density of natural fibre is half the difference between glass fibre. So, as reported by Y Zhang et al. [23], by hybridizing the flax fibre and glass fibre, the new hybrid might possess such as lightweight and higher in strength and modulus. The result shows that the hybrid gives the highest interlaminar sheer strength compare to flax fibre reinforced polymer (FFRP) and glass fibre reinforced polymer (GFRP). Thus, the structure of the fibre led to a remarkable fibre bridging and improved the interlaminar properties.

A. Des Morias et al. [8] stated that there will be no fibre bridging occurred in the $[0^\circ/90^\circ]_{12}$ specimens. This is because the measured Mode I critical strain energy release rates $G_{IC}$ were higher compared to $[0^\circ]_{24}$ specimens. Transverse cracking often occurs when the specimens have a high interlaminar fracture toughness. Although the major problem for multidirectional laminates is the development of the interplay damage and it is often associated with fibre bridging [7], in the case of
\(\Theta/\Theta\) and \(\Theta/-\Theta\) interfaces, transverse cracking promotes substantially fibre bridging, which is believed to result in high toughness values.

As referring to K Kim and L Ye, the value of \(G_{IC}\) for interlock weft knitted were a lot higher than uni-weave and hybrid. The production of hybrid composite is by stacking knitted and uni-weave composite together. The \(G_{IC}\) values for the interlock weft knitted increasing rapidly with the increased of crack length at the initial stage but fluctuated at the final stage, compare to hybrid and uni-weave composite which the values are almost constant. The fluctuate of the knitted composite means that the unstable fracture occur may cause by the difference of micro-structure which resulting from the non-uniform preform lay-up process. Moreover, the \(G_{IC}\) value for hybrid are higher than the uni-weave composite. This is because of the large amount of fibre bundles between the adjacent plies travel during manufacturing process, causing non-unique delamination planes. Furthermore, both the knitted and hybrid composites can be characterized as the wavy laminae with no distinct interlaminar layer between the plies. These wavy laminae structure can lead to a higher interlaminar fracture toughness in comparisons to uni-weave[24].

| Author                             | Material                                                                 | Condition | \(G_{IC}\) Value (J/m\(^2\)) |
|------------------------------------|--------------------------------------------------------------------------|-----------|-------------------------------|
| F. A. Almansour, H. N. Dhakal, and Z. Y. Zhang[17] | FVE \~ Flax fibre reinforced vinyl ester                                | MBT       | Wet 2683.13                   |
|                                    |                                                                          | MCC       | Dry 3578.60                   |
|                                    |                                                                          | CC        | Wet 2749.21                   |
|                                    |                                                                          |           | Dry 3740.02                   |
|                                    | FBVEu \~ Flax fibre hybridised basalt reinforced vinyl ester unstitched | MBT       | Wet 2821.70                   |
|                                    |                                                                          | MCC       | Dry 4290.42                   |
|                                    |                                                                          | CC        | Wet 2749.21                   |
|                                    |                                                                          |           | Dry 3740.02                   |
|                                    | FBVEs \~ Flax fibre hybridised basalt reinforced vinyl ester stitched    | MBT       | Wet 2806.11                   |
|                                    |                                                                          | MCC       | Dry 2669.90                   |
|                                    |                                                                          | CC        | Wet 3096.85                   |
|                                    |                                                                          |           | Dry 3113.49                   |
| M. Pinto et al [21]                | Jute/epoxy (Silane Treated)                                              | Weave     | Flock 1400                    |
|                                    |                                                                          |           | No flock 800                  |
|                                    |                                                                          | UD        | Flock 1000                    |
|                                    |                                                                          |           | No Flock 600                  |
| A. De. Morais et el [8]            | Carbon/epoxy \([0^\circ/90^\circ]\)                                    |           | 1295                          |
|                                    |                                                                          | \([0^\circ]_{24}\) | 369                          |
| Zulkifli R. et el [1]              | Silk/polyester                                                           |           | 847                            |
|                                    | 8 plies                                                                 | 10 plies  | 1530                          |
|                                    | 12 plies                                                                | 1638      | 1872                          |
| P. Suppakul and S. Bandyopadadyay[11] | E-glass/vinyl ester                                                  | Plain     | MBT 450                        |
|                                    | weave                                                                   | CC        | 500                            |
|                                    | Twill                                                                   | MBT       | 1400                           |
|                                    | weave                                                                   | CC        | 1600                           |
|                                    | Quadrant                                                                | MBT       | 850                            |
4. Conclusion
In conclusion, the Mode-I double cantilever beam testing shows a promising insight on delamination resistance. Based on past research as shown in table 1, the glass and carbon fibre gives lower interlaminar fracture toughness in comparisons to natural fibre such as flax, jute and silk. This is because of the mismatch coefficient of the glass and carbon fibre. The structure of the fibre has a large effect on the interlaminar fracture toughness, which means the structure of the fibre can lead to an improvement of fibre bridging and consequently increase the interlaminar fracture toughness.

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