Fracture Toughness Prediction of Composite Materials

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***Abstract*—This paper investigate the fracture toughness prediction of composite materials. A technique for monitoring and predicting the fracture point of composite materials is developed via experimental study. Samples of a composite approved for use in aerospace applications in accordance with EASA Part-145 are tested with a Zwick Z10 in order to determine the ultimate tensile strength. Several sample groups were introduced with the inclusion of size, production method, and lamination structure in order to identify any undue correlation. Data collected then analysed in order to identify the material nature. All information sets are used to identify the critical stress intensity factor, using a modified Griffith equation. Finally, this investigation present a full data set reflecting the fracture point of the material, which may be used for material selection reference purposes.**

Keywords—Composite; fracture toughnesst; monitoring; material analysis ; fracture point.

I. Introduction

The burgeoning interest and number of applications of composite materials has gained a considerable amount of research and development from of scientific sectors, most notably the aviation industry. Aerospace grade composites currently cost more to produce and manufacture than the vast majority of materials for similar applications, so it is important to prevent undue replacement and life limiting damage. Impact damage and wear life of a material is hence an important feature to understand when reviewing the cost effectiveness and lifespan operations of a new aircraft component, or for a modification of an in-service component.

An investigation into a technique for monitoring and predicting the fracture point of composite materials would therefore have a significant impact and usage for current consumers for the considerations related to material selection. The growing demand for better material selection and the increasing concern about the safety led to the significant research and development work on the nature of composites and fracture mechanics. For example, delamination appears to be the main focal as ‘the effect of delamination in impact [1] is often demonstrated as the main weakness of modern composites”. However, more recent studies [2], [3] illustrate the most common advancement to be based on rigorous and repeat testing of samples or material modelling to create set values of fracture points for a given material. This is not only time consuming, but impacts potential advancements by the limitations this would place on data gathering. Two main studies [4], [5] that consider the development of a novel live failure detection method for composite material act as an important point of reference for the subject study.

Previous theories and studies mainly focused on fracture in brittle materials. Griffith (1893–1963) is well known for his pioneering research of fractures in brittle materials. While other researchers such as Inglis [6] had delved into this area, there was still a mathematical difficulty; at the limits of the considered sharp crack, the effective stresses would approach infinity at the leading tip of the crack. This would indicate that the material under study would have zero or near to zero strength.

Griffith attempted to correct this by employing an energy-balance approach that “has become one of the most famous developments in materials science” [7]. This delve into fracture energy attempted to provide a solution for the difference in values for applied force between the fracturing of glass and the theoretical values for splitting the atomic bonds of the same. However, the work done by Inglis, suggested that these values should be the same. This discrepancy is theorised to be due to minute defects in brittle materials causing a lower the fracture strength of the materials. [8].

In 1957, Irwin built further on this theory [7] by introducing the critical Stress Intensity Factor, Kc. This describes stress at the crack tip, in order for a fracture to occur, the critical stress intensity factor must be reached. (KIC).

These studies represented the drive for a universal crack initiation identification method across an array of materials. However, the applications all held a reliance on a set material identification as a brittle or ductile fabrication. A consideration must be put also on the 60-year potential improvements in material studies since Irwin's findings. Classical Lamination Theory [7] gave stress and moment resultants for a subject composite, but gave limited applications for fracture point identification due to the need to individually model each plane and lamina. (FEA method).

This work consider an effective method of monitoring and predicting the fracture point of composite materials with reference to overall cost effectiveness. An investigation of fracture toughness and the identification of fracture point for material selection is also carried out via experimental study.

Samples of a composite approved for use in aerospace applications in accordance with EASA Part-145 are tested with a Zwick Z10 in order to determine the ultimate tensile strength. Several sample groups were introduced with the inclusion of size, production method, and lamination structure in order to identify any undue correlation.

Data collected may then be analysed in order to identify the material nature. All information sets will be used to identify the critical stress intensity factor, using a modified Griffith equation. This investigation will present as the final results a full data set reflecting the fracture point of the material, which may be used for reference purposes. In this work, cost effectiveness, safety, consumers and the industry are considered as the key performances measures. An effective method of monitoring and predicting the fracture point of composite materials is worth investigating as this would improve overall cost effectiveness.

The material within this studies' area of investigation covers the top three segments for current price per kg. [9]. The ability to predict or determine accurately the failure point of composites allows for a better comparison with more commonly used casted materials, allowing for the most appropriate material to be selected in regards to use and price for each given application. To better demonstrate this, most grades of steel have already been mapped in terms of fracture points under stress, in the same way this study investigates composite materials. As an example, Steel Alloy 4340 - Oil-quenched and tempered (@315 °C) first fractures under a much higher applied forces than Steel Alloy A36 [10], but the latter is approximately five times cheaper per kilogram. Hence, the knowledge of the material capabilities allows for the cheapest material to be selected that meets design requirements

Safety for consumers and users may be improved via knowledge of the fracture points of the subject materials. To prevent critical failure, the use of composite materials should be applied only when the applied situational forces will not be at the point of causing a fracture. A good example of this is seen within high-specification bicycles, where a number of high-readership news organisations have recently reported on accidents caused by unexpected critical failures of the carbon fiber frames. [11]. This not only causes a significant risk to the person using this item, but also reflects negatively on the company name, and may affect overall profits. This may cause concern for other industries looking to adapt composite materials to their own standards, as the lack of currently available data on the failure points and effect of such introduces unknown variables with regards to safety and regulation. To illustrate this, while the uses and application of composite materials within the aviation industry is increasing [12], it is limited by dated and heavily cautious regulating bodies. For example, the Federal Aviation Authority (FAA) still imposes restrictions via AC 20-107A, Composite Aircraft Structure, released in April 25, 1984.

The composites industry overall is also expanding hugely, as new materials, processes and applications are developed continuously; from using hybrid virgin and recycled fibers to faster and more automated manufacturing. Globally, the composites materials market is increasing at 5% per year, and the UK composites product market was estimated at £2.3bn in 2015, and could grow to £12bn by 2030. [9]

In this work, fracture analysis are carried out for the selected materials, in order to predict the fracture toughness. In addition, a simple cost/benefit analysis also carried out to help lower the overall cost for consumers.

II. Material Selection and Fracture Analysis

Composites are materials fabricated with two or more materials, and the combination of such gives the result properties unique to the composite, and often differing from the base components. The components do not blend or merge and should be easily distinguishable. 'Composite materials have a bulk phase, which is continuous, called the matrix; and a dispersed, non-continuous, phase called the reinforcement' [12]. Fiber Reinforced Composites (FRC) (Also known as Polymer Matrix composites) are a material composed of either glass or carbon fibers as the filament reinforcement with a plastic resin matrix. The structure composes of multiple "layers of unidirectional non-woven fibers alternated with one or more layers of woven fibers, preferably in a satin, embedded in a plastics matrix." [13] "Thus FRCs are classified into two groups: long (continuous) fiber reinforced composites and short (discontinuous) fiber reinforced composites". [14] Continuous fiber composites have long fibers uniformly oriented in order to enhance strength properties.

Fractures are caused when an appropriate amount of stress is induced in a component material, causing the material to break into two or more sections. The fracture can be classified either as "ductile or brittle, depending upon whether or not plastic deformation of the material before any catastrophic failure". [15]

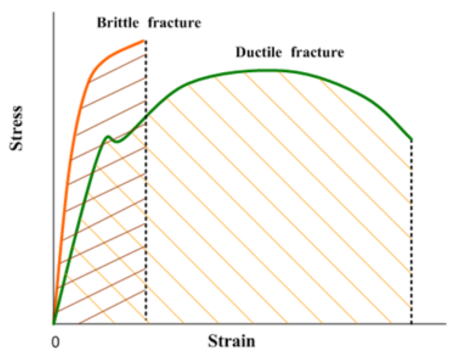

Fig 1: Stress against strain curve for comparing brittle and ductile fractures.[2]

Ductile fractures can be identified by significant plastic deformation and are usually associated with excessive or force or overload (see, Fig.1). Errors in manufacture or design are the normal causes of this fracture. Ductile fractures are associated with overload of the structure or large discontinuities. A ductile failure would also be proceeded by both elastic and plastic deformation. Brittle fractures on the other hand is a separation that occurs "without appreciable prior plastic deformation". [16]. This category of defect is usually caused by underlying issues with the material, or prior damage that develops over time.

In order to analysis the materials properties, it is important to understand how the various mechanical properties are measured and represent, since they may be used to design structures/components using predetermined materials such that unacceptable levels of deformation and/ or failure will not occur. The load – deformation characteristics are dependent on the specimen size. Therefore, study of the stress-strain relationship of the materials will give an insight to the problems associated with it. In general, the stress σ is defined as;

$$\sigma = \frac{F}{A_0} \qquad (1)$$

where, F is the instantaneous load applied perpendicular to the specimen cross section and A_0 is the original cross-sectional area before any load is applied. Figure. 2 shows the schematic diagram of the apparatus used to conduct stress-strain tests [17]. The specimen is elongated by the moving crosshead; load cell and extensometer measure, respectively, the magnitude of the applied load and the elongation.

The strain e is given by;

$$e = \Delta L / L \qquad (2)$$

and $\Delta L = l - L$

In which L is the original length before any load is applied, and l is the instantaneous length. ΔL is the deformation elongation or change in length at some instant, as referenced to the original length.

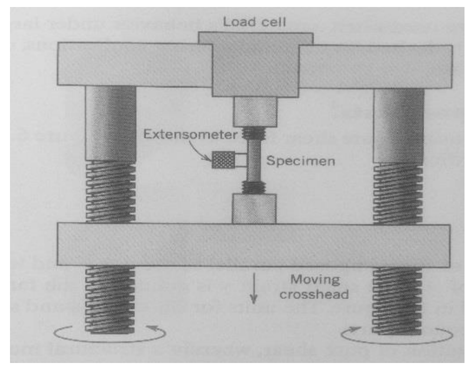

Fig.2. Stress-strain test equipment

Due to the strength of the material, when the deformation occur, the cross-sectional area is decreasing rapidly within the neck region, and hence the point of contact. This results in a reduction in the load-bearing capacity of the specimen. The stress, as computed from (1), is on the basis of the original cross-sectional area before any deformation, and does not take into account this reduction in area at the neck. Therefore, a true stress-strain relationship is obtained as follows;

The true stress σ_T is defined as

$$\sigma_T = \frac{F}{A_d} \qquad (3)$$

where A_d is the instantaneous cross-sectional area of which deformation is occurring.

and the true strain e_T is given by

$$e_T = \ln(l/L) \qquad (4)$$

If no volume change occurs during deformation, then

$$A_d l = A_0 L \qquad (5)$$

and

$$\sigma_T = \sigma(1+e) \qquad (6)$$

$$e_T = \ln(1+e) \qquad (7)$$

It is important to note that the equations (6) and (7) are valid only to the onset of necking.

This analyses is used to conduct a comparative stress-strain behaviours, and select a suitable material and quantities to use for the required design . It is important to note that for the design problem, the stress intensity factor need to be calculated and its critical value is a key parameter.

The stress intensity factor (K) is used in fracture mechanics to predict the stress state at the vicinity of a crack caused by external load and is useful for providing an indication of the likelihood of failure (crack propagation).

The stress intensity factor (K) is given by;

$$K = Y \times \sigma \times \sqrt{(\pi a)} \quad (8)$$

Where, Y depends on the geometries of the crack, specimen and nature of loading. σ is the applied tensile stress, and a is the given crack dimension. The critical value of K is the fracture toughness and is defined as the resistance of a material against fracture (crack propagation). The condition for crack propagation σ_c of a given material can be determine by using Griffith's theory of fracture. Where σ_c is;

$$\sqrt{\left(\frac{2\gamma E}{\pi c}\right)} \quad (9)$$

and σ_c is the externally applied "critical" stress to cause crack propagation (N/m^2), and is dependent on; γ the energy required to create a unit of new surface area (J/m^2), and E the modulus of elasticity (N/m^2) of the chosen material and c is the given crack length (m). In most materials there is a degree of ductility thus the equation needs to take into account the energy spent to cause plastic deformation. Thus need to substitute 2γ (for brittle fracture) with $2(\gamma + \gamma_p)$ to account for additional energy required for plastic deformation per unit area of crack.

In this study, the subject composite is of a continuous fibre composition, and is approved for usage in various aviation applications in accordance with EASA 145-b regulations. The material selected for this study, has the respective similar material properties to the authors previous work [5]. Therefore, it can be used as the main comparative work due to the direct comparisons that may be drawn with regards to composite testing.

III. Methodology

In order to determine the fracture toughness and fracture point of the selected material, many experiments have been conducted on multiple samples with different layers. The batches included a set of 7-layer thick and 4-layer thick composites. These layer combinations were chosen as these are the minimum and maximum restrictions for the application of the subject material. Further, the results to be compared [5] utilised composite samples of 4 layers thick composites.

A metal testing bench was cleaned with solvent and a non-permeated release material was sealed to the surface of area 600mm by 500mm. The reinforcement was cut into panels of the same dimension but at 45-degree alterations in alignment. As discussed earlier within this paper, this adds strength to the material. Batches of the resin were mixed, of 100-part resin to 30-part hardener. Each layer was fully coated in resin and layered onto the bench. A permeated release fabric, followed by an absorbent mesh, was then placed on top of the composite. This allows for excess resin to be removed from the composite during the curing cycle. The total set was then sealed with a thin plastic and a release valve and suction tube punched through, forming a vacuum around the entirety of the setting composite. A 24-hour curing period was then allowed before manufacturing Figure 3 shows the sample of a manufactured composite.

Fig 3: Image of manufactured composite

IV. Results and Discussion

A 3-point flexural test was set up and run on a Zweick Z010 machine for all different samples. These Specimens used as part of the set-up process to determine the final testing criteria. On comparison, the 4-ply and 7-ply test samples were divided into three different types, which are; Factory (F) and Manual (M) made and Defective (D) samples.

All measurements were taken from at least 3 points on the sample, and the average given. Measurements were taken with a calibrated Vernier caliper, to 0.001 inches degree of accuracy. The rough and sharp edges may also have an impact on the sample fracture point. To track any possible affect, the cut evenness or variation in width has been recorded on a scale of 1-10 (Least to most affect). The date for the 4-ply and 7-ply test samples is given in Table 1.

Table 1: Samples date for the three different types

Specimen	Fmax (N)	dL at Fmax(mm)
5 (7F)	203.0397339	9.973643303
6 (7M)	158.2297516	10.74029922
7 (7F)	201.5578156	11.99035072
8 (7M)	159.3256073	10.25703335
9 (7D)	218.7993927	12.58197498
10 (4F)	51.25204468	13.88200283
11 (4M)	72.86940765	14.1570673
12 (4M)	68.65861511	13.94040394
13 (4D)	83.12310791	12.07371998

On comparison, the 4-ply and 7-ply test samples exhibit two very distinct graphs (see Figures 4 – 8). The 7-ply has presented with an expected failure graph, with a similar format to as discussed in section 2 (see, Fig. 1).

This also reflects similarly to the material test presented in [5]. The results in [5] demonstrated a clear limit of proportionality, followed by a distinct double peak before the fracture point at approximately 1/5th added total force. Looking at the results, this could be taken to suggest that different compositions of continuous fibre composites will still perform in a similar manner under stress. By contrast, composite samples of 4-ply performed less well. On logical review it would be expected for the material to present the same graph format, but at a 57% rate of the 7-ply, due to material thickness. However, the 4-ply samples indicate results [5] similar to a more ductile material. Brittle materials have low value of fracture toughness and vulnerable to catastrophic failure. Conversely, facture toughness values for ductile materials are large. Therefore, this type of tests and technique is useful in predicting catastrophic failure in materials having intermediate ductilities.

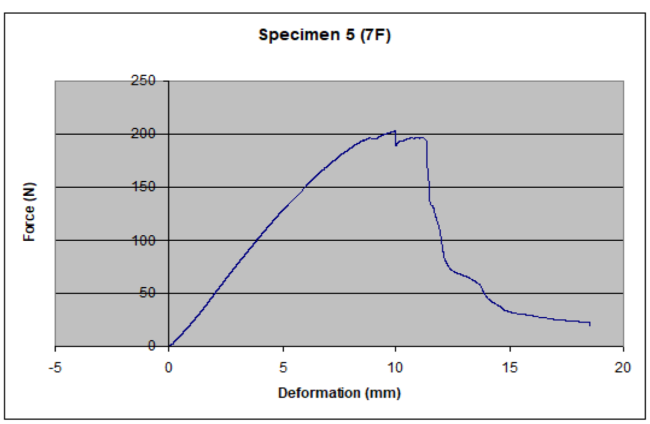

Fig 4: Force (N) against deformation (mm) graph for Specimen 7, 7F.

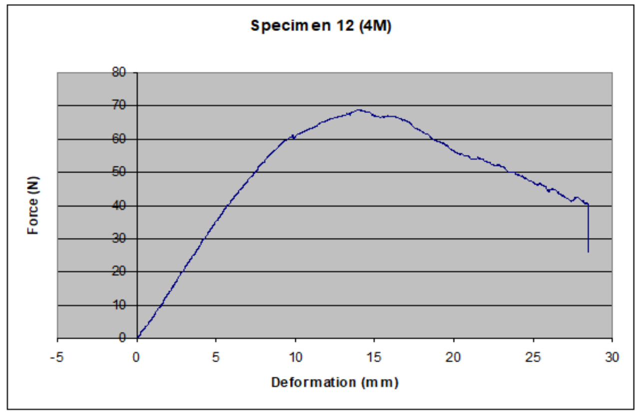

Fig.5: Force (N) against deformation (mm) graph for Specimen 12, 4M.

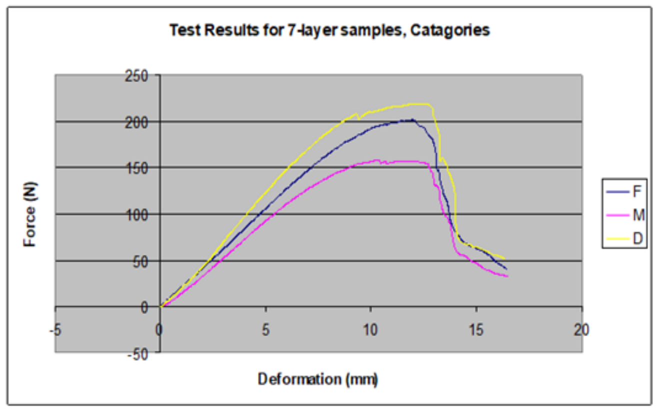

Fig. 6: Force (N) against deformation (mm) graph for all categories of the 7-layer samples.

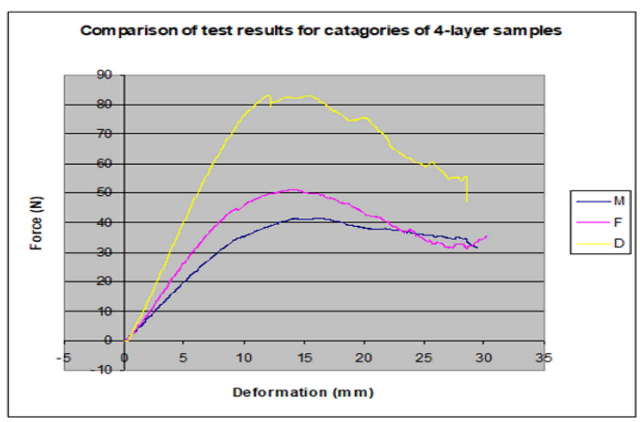

Fig. 7: Force (N) against deformation (mm) graph for all categories of the 4-layer samples.

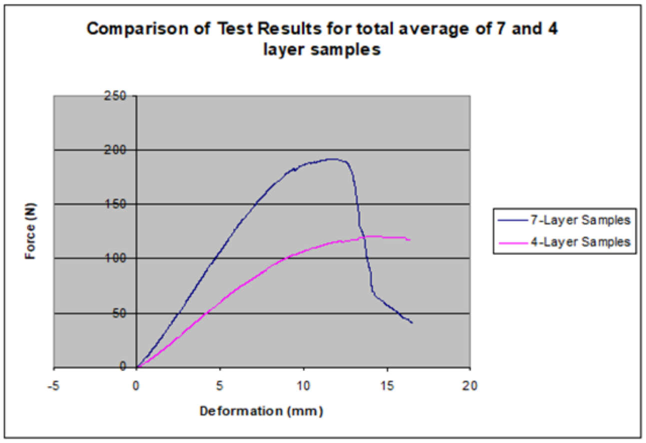

Fig. 8: Force (N) against deformation (mm) graph for the averages of 4 and 7 layer samples.

V. Concluding remarks

In this paper, an investigation of fracture toughness and the identification of fracture point for material selection is carried out. This work also, contains an experimental study to examine materials properties and to help lower the overall cost for consumers and industry. A technique for monitoring and predicting the fracture point of composite materials is developed via experimental study. Samples of a composite approved for use in aerospace applications in accordance with EASA Part-145 are tested with a Zwick Z10, hence the ultimate tensile strength is determined. Several sample groups were introduced with the inclusion of size, production method, and lamination structure in order to identify any undue correlation. Data collected then analysed in order to identify the material nature. All information sets are used to identify the fracture toughness, using a modified Griffith equation. Finally, this investigation lead to the development of a complete data set reflecting the fracture point of the material, which may be used for material selection reference purposes for critical applications of key industry such as aerospace etc.

Future work includes the development of a complete simulation model of the method and it may be useful for the simple and quick selection of the desired materials.

References

[1] M.Wisnom. The role of delamination in failure of fibre-reinforced composites. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 370(1965), pp.1850-1870, 2012.

[2] M. Koc., F. Sonmez., N. Ersoy., and K. Cinar. Failure behavior of composite laminates under four-point bending. *Journal of Composite Materials*, 50(26), pp.3679-3697, 2016.

[3] V. Kiiko, and S. Mileiko. A simple model of the fracture process zone in composites. *Composites Science and Technology*, 26(2), pp.85-94., 1986.

[4] M. Bowkett, K. Thanapalan**.** A novel live failure detection method for composite material systems *International Journal of Mechanical Engineering and Robotics Research*, Vol. 7(3), pp. 213-217, May 2018.

[5] M. Bowkett, K. Thanapalan**,** E. Constant. Failure detection of composites with control system corrective response in drone system applications. *Computers*, Vol.7(2), 23, pp. 1 -18, April, 2018.

[6] C. Inglis. *Applied mechanics for engineers*. New York: Dover Publications, 1963.

[7] D. Apelian. Looking beyond the last 50 years: The future of materials science and engineering. *JOM*, 59(2), pp.65-73., 2007

[8] T. Boukharouba., M. Elboujdaini., and G. Pluvinage. Damage and fracture mechanics. [S.l.]: Springer, 2009

[9] J. Roox. Cost, Composites UK. [online] Compositesuk.co.uk. Available at:https://compositesuk.co.uk/composite-materials/properties/costs. 2019.

[10] W. D. Callister, Jr. Materials Science and Engineering An Introduction,. *John Wiley & Sons, Inc*, 2015.

[11] M. Bowkett, K. Thanapalan. Comparative analysis of failure detection methods of composites materials systems. *Systems Science & Control Engineering: An Open Access Journal*, Vol. 5(1), pp. 168-177, 2017.

[12] B. Åström. *Manufacturing of polymer composites*. London: Chapman & Hall., 1997

[13] P.T. curtis and S.M. Bishop. An assessment of the potential of woven carbon fiber-reinforced plastics for high performance applications, *Composites*, Vol. 15(4), pp.259-265, 1984

[14] R.Nariandar , M.Nair, K.P. Dasan. Hybrid Polymer Composites, 2014

[15] M. Abdul Maleque. *Materials Selection and Design*. Singapore: Springer Verlag, Singapore, 2013.

[16] J. Field. Brittle fracture: Its study and application, Contemporary Physics. Contemporary Physics, 1971.

[17] H. W. Hayden, W.G. Moffatt and J. Wulff, “The structure and properties of materials: Mechanical behavior”, John Wiley & Sons, New York, 1965