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Relation between interlaminar damage extension and fiber orientation with acoustic signal: quasi-static and cyclic loading

Guaratinguetá – SP
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Relation between interlaminar damage extension and fiber orientation with acoustic signal: quasi-static and cyclic loading

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Orientador: Prof. Dr. Herman Jacobus Cornelis Voorwald
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“A person who never made a mistake never tried anything new”

Albert Einstein

ABSTRACT

Fiber-reinforced polymer (FRP) composites have a great potential to replace metals in applications that require lighter components and structures since these materials can reach high in-plane properties of specific strength and stiffness. The FRP composites frequently used in engineering structures are laminates comprised of continuous-fiber plies without reinforcement in the thickness direction, which reduces the material's interlaminar strength leading to delamination susceptibility. Most of these structures operate under long-term cyclic loadings, resulting in a gradual delamination propagation. Hence, extensive research has been conducted to understand and predict fatigue delamination growth in FRPs over the past decades. However, most of the efforts were concentrated on the prediction itself rather than attributing physical explanations to the mechanisms associated with the propagation process. In order to contribute to this field, this research focuses on the assessment of delamination within a single loading cycle in FRP using double cantilever beam specimens with varying stress ratios (R). The acoustic emission (AE) technique was used to investigate damage propagation, and a new methodology was developed to quantify the strain energy release due to crack growth in fatigue. In addition, the development of fiber bridging in the crack propagation through different interface configurations was investigated with focus on the influence of bridging on the strain energy released. Results showed that under high R-ratios, the load cycle spends an increased time above the threshold energy (U_{th}: minimum amount of energy required to damage development) in terms of total strain energy, which affected the damage distribution within a single loading cycle. Besides that, the strain energy release behavior within the fatigue cycles indicated that different damage mechanisms are activated in different increments of the load cycle associated with different energy thresholds. The presence of multiple energy thresholds indicated that the application of different loading cycles results in distinct resistances to damage propagation (dU/dA) depending on which energy threshold is crossed. For example, the rupture of bridging fibers may impact dU/dA when the threshold energy to activate this damage mechanism is exceeded. It was observed that the angle of the fibers (α) in the interface where the crack propagates affected the stresses acting on the bridging fibers, leading to the rupture of more fibers when α was increased. In other words, α eases the activation of this specific damage mechanism. Hence, once fiber breakage releases strain energy, the material resistance to delamination growth is affected.

KEYWORDS: Stress ratio. Fractography. Fracture mechanics. Laminates.

RESUMO

Materiais compósitos de matrizes poliméricas reforçados por fibras possuem grande potencial para substituir os metais em aplicações estruturais em que o objetivo seja a obtenção de estruturas leves devido suas elevadas propriedades mecânicas específicas. Os compósitos poliméricos reforçados por fibras voltados para aplicação estrutural são compostos por camadas de fibras (laminados). Portanto, não possuem reforço na direção da espessura, o que reduz a resistência interlaminar do material, tornando-o suscetível a delaminação. Consequentemente, pesquisas têm sido realizadas para uma melhor compreensão do fenômeno e o desenvolvimento de modelos capazes de prever a delaminação em regime cíclico. Entretanto, o foco das pesquisas tem sido restrito ao desenvolvimento de modelos, enquanto o entendimento físico associado ao fenômeno se tornou um objetivo secundário. Portanto, esta pesquisa tem o foco no estudo da delaminação no curso do ciclo de carregamento em fadiga. A técnica de emissão acústica foi utilizada para avaliação da delaminação e para o desenvolvimento de uma metodologia para quantificar a liberação de energia de deformação elástica devido a propagação de dano. Além disso, o desenvolvimento de pontes de fibra durante a propagação da delaminação por interfaces com diferentes configurações foi avaliado com foco na influência desses mecanismos na liberação de energia. Os resultados mostraram que uma elevada razão de carregamento aumenta o tempo em que o ciclo permanece acima do limite de energia necessário para propagação de dano (U_{th}) em termos de energias totais, afetando a distribuição de dano ao longo do ciclo de carregamento. A liberação de energia de deformação ao longo do ciclo de carregamento indicou que diferentes mecanismos de dano são ativados em diferentes regiões do ciclo pois necessitam de específicos níveis de energia para ocorrerem. A presença de múltiplos limites de energia (U_{th}) associados a diferentes mecanismos de dano significa que o material pode apresentar diferentes resistências à delaminação. Esta variação se deve a ativação de diferentes mecanismos de acordo com o ciclo de carregamento aplicado dependendo da quantidade de U_{th} ultrapassados. Por exemplo, a ruptura de pontes de fibra pode afetar a liberação de energia de deformação quando as condições mínimas para a ativação desse mecanismo são excedidas. Foi observado que o aumento do ângulo (α) das fibras na interface em que a trinca se propaga eleva as tensões atuantes na fibra, aumentando o número de eventos de ruptura de pontes de fibra. Como esse mecanismo é associado a uma liberação de energia de deformação, a resistência do material é alterada.

PALAVRAS-CHAVE: Razão de carregamento. Fractografia. Mecânica da fratura. Laminado.

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SUMMARY

1 INTRODUCTION

1.1 CRACK PROPAGATION THEORY FROM GRIFFITH UNTIL PARIS: THE GAP BETWEEN EMPIRICAL AND PHYSICAL UNDERSTANDING

One of the most critical questions that engineers have to deal with during the design of any structure is how reliable is the approach to ensure a safe time in which the structure can operate with or without damages. The failure or rupture of a structure usually occurs through a crack propagation, which is nucleated and propagated due to the application of quasi-static, dynamic or cyclic external loadings to the structure. In the last decades, innumerous crack propagation models and different techniques were developed to predict the life of components containing cracks. The vast majority of these life prediction models rely on the linear elastic fracture mechanics (LEFM) theory (PASCOE; ALDERLIESTEN; BENEDICTUS, 2013).

The first relevant article related to crack propagation was developed by Griffith (GRIFFITH, 1921), which is considered the basis of the LEFM theory. Griffith's theory is based on an energy balance approach, in which an amount of energy must be consumed and released for crack propagation. The consumed energy corresponds to the energy required to create new fracture surfaces, which is quantified by the surface energy of the material multiplied by the area of new fracture surfaces. The released energy corresponds to the elastic strain energy release from the surrounding material (GRIFFITH, 1921). It is important to mention that Griffith's work was restricted to perfectly brittle materials under fixed-grip and quasi-static load conditions. Hence, several researchers made efforts to extend the theory first proposed by Griffith to a broader range of materials and loading conditions.

The first significant addition to Griffith's work was independently made by Orowan (OROWAN, 1949) and Irwin (IRWIN, 1948), extending the energy balance concept to ductile materials. When a crack grows in a perfectly brittle material, the energy consumption is restricted to creating new fracture surfaces. However, ductile materials present a plastic deformation in the vicinity of the crack tip, a process that also requires a certain amount of energy to occur. Therefore, the energy consumption for ductile materials corresponds to a sum of the energies consumed by plastic deformation and the creation of new fracture surfaces.

With the determination of the mechanisms responsible for energy consumption during crack propagation, Irwin and Kies formalized the energy balance of Griffith mathematically, as presented in Eq. 1.1 (IRWIN; KIES, 1954):

$$\frac{dF}{dA}-\frac{dU}{dA}=\frac{d(W_s+W_p)}{dA}+\frac{dE_k}{dA} \tag{1.1}$$

in which F is the work applied in the body by external forces, U is the strain energy in the body, W_s is the energy consumed by the creation of new fracture surfaces, W_p is the energy consumed by the plastic deformation at the vicinity of the crack tip, E_k is the kinetic energy, and A is the crack surface area.

The left side of Eq. 1.1 is the energy available for crack propagation, also known as the strain energy release rate (*SERR* or G), while the right side corresponds to the energy required for any crack increment, in which kinetic energy term is negligible in quasi-static condition. This minimum energy required to crack propagation can be referred to as a critical energy value (G_c), interpreted as the material resistance to crack propagation. Therefore, Eq. 1.1 works as a stability criterion for crack propagation in which a stable propagation occurs when $G = G_c$, and an unstable propagation occurs when $G > G_c$. However, one should note that the concept of G_c is valid only for quasi-static load conditions, and should not be directly extended to cyclic loading conditions. When a body containing a crack is submitted to cyclic loadings, the crack propagates with values of G considerably lower than the critical value (G_c). Hence, many researchers focused on explain and predict the fatigue crack growth behavior in fatigue.

Innumerous models have been proposed so far to predict crack growth in fatigue. Among them, the work of Paris and co-workers was the most established and has been the basis for most of the LEFM based-models developed after that. According to Paris, the fatigue crack growth (FCG) is governed by the crack tip stress field rather than the far-field stresses. This stress field surrounding the crack tip showed to be well represented by the stress intensity factor (*SIF* or K), and its range ($\Delta K = K_{max} - K_{min}$) was used as a similitude parameter to develop the Paris relation as follows (PARIS, 1963; PARIS; GOMEZ; ANDERSON, 1961):

$$\frac{da}{dN}=C\Delta K^n \tag{1.2}$$

where a is the crack length, N is the number of cycles, and C and n are curve fitting parameters.

Paris' work was developed based on the FCG in metals but was adopted to describe the propagation of cracks and delamination in laminated composites and joint with adhesive bonds. These materials present a non-homogeneous structure, which makes the calculation of K extremely difficult. Thus, K was replaced by G as the similitude parameter to study fatigue delamination growth (FDG).

The equivalence between the *SERR* and the *SIF* was demonstrated by Irwing in Eq. 1.3 (IRWIN, 1957):

$$G = \frac{K^2}{E'} \tag{1.3}$$

Plane stress: $E' = E$ (1.4)

Plane strain: $G = \frac{E}{1-v^2}$ (1.5)

where *E* is the Young's modulus of the material, and *v* is the Poisson ratio.

Irwin's correlation in Eq. 1.3 means that two different principles could describe crack propagation. The stress intensity factor (*K*) relies on the stress field surrounding the crack tip, while *G* is based on the strain energy state of the body. The Paris relation was first developed based on the concept that the crack tip stress field governs the FCG. When *G* replaces *K*, an energy parameter is used to describe the stress state at the crack tip, making the similitude basis of these FCG models unclear (PASCOE, 2016).

Besides, a crack tip will always present a stress field quantified by *K*, which means a "real" quantity. On the other hand, *G* is defined as the amount of strain energy released due to crack propagation, and when no propagation occurs, the value of *G* becomes a supposition of the strain energy that would be released in case of damage propagation, which means a "virtual" quantity. Therefore, according to Eq. 1.3 proposed by Irwin, the crack tip stress state can be measured by a "virtual" amount of energy described by *G* when no damage propagates (PASCOE; ALDERLIESTEN; BENEDICTUS, 2015).

Models to predict crack propagation in composites have been developed for almost half a century. However, most of the efforts were concentrated only on the prediction itself rather than attributing physical explanations to the mechanisms associated with the process. This mindset leads to models' development through the mathematical adjustment of a curve to the experimental data, which requires extensive test campaigns. Additionally, some factors might affect the crack propagation behavior, e. g. the *R*-ratio variation, a combination of loads, and the temperature. Aiming to account for these factors, most researchers have focused on changing the similitude parameter of the fundamental relation, increasing the number of empirical relations with a marginal understanding of the phenomenon itself (PASCOE, 2016). The lack of consensus on which equation or similitude basis should be adopted to predict FCG slows down technology advances. Thus, some backward steps are required to build a solid foundation before any step further towards developing more empirical FCG prediction models.

1.2 RESEARCH OBJECTIVES

The main goal of this research is to explain the underlying physics of the fatigue delamination growth (FDG) in fiber-reinforced polymers (FRP). The research focused on the investigation of the micro-mechanisms developed during crack propagation using the AE technique, which led to the central question of this work:

- **How does damage propagate within the loading cycles in fatigue?**

This first question originated other questions regarding crack propagation within a single loading cycle, which is addressed in Chapter 2:

- Is there an energy threshold within the loading cycle to enable damage propagation?
- How is the damage distribution along a single loading cycle?
- Does the *R*-ratio variation have any influence on the damage distribution along the loading cycle?
- Does the *R*-ratio have any influence on the damage onset within the loading cycle?
- Is damage propagation continuous in fatigue?

In order to go into in-depth on this topic, the following questions were addressed in Chapter 3:

- How is the strain energy release due to damage propagation within a single loading cycle?
- What is the physical meaning of the similitude parameters most used in FDG prediction models?
- Can the AE technique be used to measure the strain energy release within the loading cycles?
- Is it possible to correlate the strain energy release with the acoustic energy release and the fracture surface features?
- Are different micro-mechanisms of damage associated with different energy thresholds to enable damage propagation within the loading cycle?

- Does the *R*-ratio variation have any influence on the strain energy release within the loading cycles?

The concepts presented in Chapters 2 and 3 were used to correlate fiber bridging with strain energy in Chapter 4, in which the following questions were addressed:

- How does fiber bridging affect the resistance to delamination growth?
- Which is the parameter that governs fiber failure?
- Does the fiber lay-up direction have any influence on the failure of bridging fibers, affecting the strain energy released due to delamination growth?
- Can the AE technique be used to identify fiber breakage in fatigue tests?
- When does fiber breakage occur: within the context of the loading cycles and during the fatigue tests?

5 FINAL CONSIDERATIONS AND FUTURE WORKS

The main objective of this research was to provide physical explanations to the phenomenon of damage propagation (more specifically delamination growth) under cyclic loading in laminate composites. The strategy to achieve this goal consisted of investigating the process of damage formation within a single loading cycle using the acoustic emission technique, which required the development of innovative methodologies. Among these methodologies, a novel correlation was established between the release of acoustic and strain energy, allowing the measurement of the strain energy released within the loading cycles due to damage propagation by means of a conversion factor to convert one energy into the other.

This methodology showed to be suitable for scientific applications under controlled testing conditions. However, the sensibility of this conversion factor to the specimen geometry and the loading conditions inhibits the use of this technique for engineering purposes. Hence, a challenge for future works is to gain knowledge on this correlation and, more specifically, comprehend how this correlation varies with different testing conditions. In the present work, a restricted number of cycles were considered in the analyses to avoid a considerable variation of both the crack growth rate and the crack length, resulting in a linear behavior between the acoustic and the strain energy released, which allowed the calculation of the conversion factor using the slope of the curve adjusted to the experimental data. Consequently, the behavior of the strain energy released within the loading cycles could be investigated by measuring the acoustic energy released due to damage formation. These results supported the hypothesis of multiple damage mechanisms activation associated with respective energy thresholds (U_{th}), which was based on the variation of the strain energy release rate in different regions of the loading cycle.

The strain energy stored in the specimen's arms varies according to the region of the loading cycle, meaning that different energy thresholds (each one associated with a specific damage mechanism) are crossed in different regions of the cycle. Therefore, if more energy thresholds are crossed, more damage mechanisms are activated, increasing the strain energy released rate within the cycle, as observed in the results presented in Chapter 3. In addition, the present research focused on proving the hypothesis of multiple energy thresholds. Consequently, the identified thresholds were not associated with a specific damage mechanism, which is a challenge for future works.

Chapter 4 gave some steps towards this direction, focusing on identifying fiber breakage within the loading cycles using the acoustic emission technique, which is a technique with a great potential for damage identification. On the other hand, using the acoustic emission technique for damage identification in fatigue presents some limitations related to the extensive amount of data created during the test, which avoids recording the waveform, inhibiting the use of frequency parameters for damage identification. Besides, reducing the detection of signals related to noise is a challenge, especially signals from friction noise, and the use of different specimen configurations could be considered.

Finally, the hypothesis of multiple energy thresholds for the activation of multiple damage mechanisms can be beneficial for developing crack growth prediction models in fatigue. In general, as discussed in Chapters 2 and 3, the literature refers to a single energy threshold to damage onset, resulting in models unable to explain the influence of both the stress ratio and the crack growth rate on the fatigue resistance curves. In the present work, the hypothesis of multiple energy thresholds showed a clear correlation between the loading cycle and the crack growth behavior, revealing the potential of this concept to originate models that reflect the real behavior of the material based on physical concepts.

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