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A mini-review on ductile fracture mechanism of cracked/notched composite elements

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A B S T R A C T

This study explores the ductile fracture mechanisms of cracked and notched composite elements, focusing on their structural integrity and failure behavior under various loading conditions. Composites are increasingly utilized in engineering applications due to their high strength-to-weight ratios and tailored properties; however, understanding the fracture processes is essential for optimizing their performance and durability. We analyze the key factors influencing ductile fracture, including material composition, notch geometry, and the influence of environmental conditions. This review aims to provide insights into the critical parameters that govern ductile failure, facilitating improved predictive models for the assessment and longevity of composite structures.

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1. Introduction

Ductile fracture mechanisms represent a critical area of study in materials science, particularly concerning composite materials that exhibit both cracked and notched configurations [1, 2]. Composite materials have become indispensable in various industries, including aerospace, automotive, and construction, due to their superior strength-to-weight ratio, corrosion resistance, and design flexibility [3, 4]. However, the presence of defects such as cracks and notches significantly impact the structural integrity and mechanical performance of composite elements [5]. These defects act as stress concentrators, initiating and propagating damage under mechanical loading, which can lead to premature failure[6, 7]. In addition, the complexity of ductile fracture in composite materials emerges from a multifaceted interplay between the matrix and reinforcement phases. Each of these components plays a crucial role in influencing the overall mechanical response of the material [8]. The matrix, typically a polymer or metal, provides a binding matrix that supports the reinforcement, which may consist of fibers or particles that confer strength and rigidity [9]. Together, they interact in a way that not only affects the load distribution and stress concentrations but also determines how the material behaves under various mechanical loads. The failure mechanisms that arise in such composites are therefore not merely a result of one phase failing but are significantly determined by the dynamic interactions between the matrix and the reinforcements, leading to the observed complexity in ductile fracture behavior [10-12]. This makes the study of crack and notch behavior in composites both challenging and essential. This mini review aims to investigate the ductile fracture mechanisms of cracked and notched composite elements, focusing on the interaction between matrix and fiber, stress distribution, and the factors influencing crack growth and

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failure modes. By gaining insights into these mechanisms, it is possible to enhance the reliability and safety of composite structures in demanding applications.

2. Overview of ductile fracture mechanisms

Ductile fracture in composites involves mechanisms that allow for non-linear deformation and gradual failure, rather than sudden catastrophic failure [13]. Their mechanism in composite materials is characterized by a sequence of processes that involve the nucleation, growth, and coalescence of voids within the material structure [14]. Fig. 1 illustrate a schematic of several failure mechanisms that are usually called 'ductile fracture'. The ductile fracture mechanisms encompass five main processes, each with distinct characteristics. Mechanism 1 occurs in very pure metals, where failure can happen without damage due to the absence of void nucleation sites. In Mechanism 2, plasticity localizes into shear bands, and as large plastic strains accumulate, voids nucleate, grow, and coalesce. Mechanism 3 involves damage nucleation occurring before macroscopic localization, where the softening induced by accumulated porosity counteracts the material's strain-hardening capacity. Mechanism 4 refers to the simultaneous occurrence of macroscopic localization and coalescence, where the onset of coalescence dictates macroscopic localization. Finally, Mechanism 5 distinguishes between large-scale coalescence localizations and those involving only a few voids, focusing on macroscopic localizations due to void growth or coalescence [14]. These mechanisms are crucial for understanding how composites behave under stress, particularly when they contain defects such as cracks or notches [15].

In contrast to brittle fracture, which occurs suddenly with little plastic deformation, ductile fracture allows for significant deformation prior to failure, providing insights into the material's toughness and resilience [16]. The initiation of ductile fracture typically begins with the nucleation of voids at stress concentrators, such as inclusions or interfaces between different phases in the composite. As the material is subjected to tensile stress, these voids grow and eventually coalesce, leading to macroscopic failure. This process is influenced by several factors, including the material's microstructure, loading conditions, and the presence of interfacial interactions between different components of the composite [17, 18]. For instance, recent studies have shown that enhancing interfacial bonding through modifications can significantly improve ductility by facilitating better load transfer and delaying the onset of fracture [19]. Moreover, the role of microstructural features is pivotal in dictating the fracture behavior of composites. The distribution and morphology of reinforcing fibers, matrix materials, and any existing flaws can profoundly affect how voids nucleate and grow [20]. Moreover, the influence of matrix materials and their interaction with reinforcing fibers is critical in dictating the fracture mechanisms [21]. Liu et al. [22] demonstrate that in 3D needle- punched C/SiC ceramic-matrix composites, damage mechanisms such as matrix cracking, fiber breakage, and pullout contribute to a nonlinear tensile response, which is essential for understanding ductile fracture behavior

3. Crack and notch behavior in composite materials

Crack and notch behavior in composite elements is a crucial aspect of understanding their durability and performance under various loading condition [23]. Composites, which typically consist of a matrix material reinforced with fibers, exhibit unique fracture characteristics due to their heterogeneous structure. When subjected to stress, cracks can initiate from defects, notches, or interfaces between different materials, leading to complex failure modes such as delamination's, fiber breakage, and matrix cracking [24, 25]. The behavior of cracks in composites is influenced by several factors, including the type of fibers used, the matrix material, and the loading environment [26]. Additionally, the interaction between cracks and the composite's microstructure plays a vital role in determining how these materials respond to stress. Advanced modeling techniques, such as finite element analysis (FEA), have been developed to simulate crack propagation and assess the structural integrity of composite materials under monotonic and cyclic loading conditions [27, 28]. Experimental studies have also highlighted the importance of environmental factors on crack behavior [29, 30]. This section provides an overview of the primary ductile fracture mechanisms observed in cracked or notched composite elements, highlighting the role of matrix properties, fiber reinforcement, and interfacial interactions.

3.1. Matrix cracking

The matrix in composite materials serves as the primary load-bearing phase and is crucial for transferring loads between fibers. Under tensile loading, the matrix can experience cracking, which is often the first mode of damage. The initiation of matrix cracks typically occurs at stress concentrations, such as those found at notches or defects [31]. These cracks can propagate through the matrix, leading to a reduction in load transfer efficiency and ultimately contributing to the overall failure of the composite. Research by Liu et al. [22] demonstrated that matrix cracking is a significant precursor to more catastrophic failure modes in 3D needle-punched composites, indicating that understanding matrix behavior is essential for predicting ductile fracture.

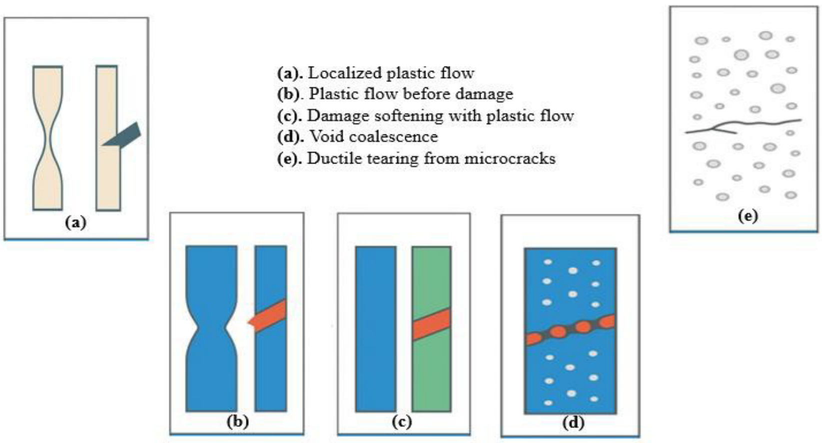

Fig. 1. Schematic of several failure mechanisms ductile fracture.

3.2. Fiber breakage and pull-out

Fibers are incorporated to enhance strength and stiffness in composite materials [32]. However, under tensile loading, fibers can also break, particularly when subjected to high stress concentrations. The breakage of fibers contributes to energy dissipation during fracture, which is a hallmark of ductile behavior [33]. Additionally, fiber pull-out mechanisms play a crucial role in enhancing the toughness of composites. When fibers are pulled out of the matrix, they absorb energy, which delays crack propagation and increases the overall fracture resistance of the material [34].

3.3. Interfacial debonding

The interface between the fiber and matrix is critical in determining the mechanical performance of composites. Interfacial debonding occurs when the adhesive bond between the fiber and matrix fails, allowing for relative motion between these two phases [35]. This mechanism can contribute to ductility by allowing for energy dissipation through the sliding of fibers within the matrix [36]. For instance, in applications such as reinforced concrete, the use of steel fibers can enhance ductility and toughness. When subjected to tensile loads, if the bond between the steel fibers and concrete weakens, the fibers may slide within the matrix rather than break. This sliding action allows for energy absorption, which can help prevent sudden failure of the structure [37, 38].

3.4. Fiber bridging

Fiber bridging is another critical mechanism that contributes to ductile fracture behavior in composites. When a crack propagates through a composite, fibers that span the crack can bridge the gap, providing additional load-bearing capacity and delaying crack propagation [39]. This mechanism is particularly effective in improving the toughness of composites, as it allows for continued load transfer even after the initial crack has formed [40]. A notable example of fiber bridging in civil engineering is found in Engineered Cementitious Composites (ECC). Review by VC Li [41] demonstrated that ECC exhibits significant ductility and toughness due to its unique fiber bridging capabilities. The fibers within the ECC matrix can bridge cracks, thus preventing rapid failure and allowing for energy dissipation during loading conditions.

3.5. Temperature and rate effects

The mechanical behavior of composites is significantly influenced by temperature and loading rates [42]. Elevated temperatures can reduce the strength and stiffness of polymer-based composites, leading to premature failure, especially in structures exposed to high heat [43]. Conversely, high loading rates may enhance the apparent strength of some materials due to strain rate sensitivity, but can also result in brittle failure if not properly accounted [44].

4. Factors affecting fracture mechanisms

Several factors influence the ductile fracture mechanism in composite materials. Material properties such as yield strength, tensile strength, and hardness play a significant role [45, 46]. High yield strength materials can withstand substantial stress without experiencing permanent deformation, reducing the likelihood of ductile fracture [47].

Conversely, excessive hardness may increase brittleness, making a material more prone to sudden failure. Grain size and orientation are also crucial; finer grains can enhance ductility by providing more slip systems for dislocation movement, which aids in energy dissipation during deformation [48]. The rate of loading is another important factor; slower loading rates allow more time for plastic deformation to occur, enhancing ductility. Rapid loading can lead to premature failure even in materials that are typically ductile. Environmental factors such as temperature significantly affect ductile fracture behavior. At lower temperatures, materials may exhibit increased brittleness and a higher propensity for sudden failure [49, 50]. In contrast, elevated temperatures generally promote greater plastic deformation before fracture occurs. Additionally, the history of stress and strain experienced by a material can led to fatigue damage over time. Repeated loading cycles may cause localized structural damage that can culminate in ductile fracture under stress levels that would otherwise be acceptable [51-53].

5. Conclusion

The study of ductile fracture mechanisms in cracked or notched composite elements is essential for enhancing the reliability and performance of engineering materials. This mini-review has underscored the complex interplay of factors such as material properties, environmental conditions, loading scenarios, and microstructural characteristics that influence ductile fracture behavior. A deeper understanding of these mechanisms is crucial for predicting failure modes and improving the design of composite materials in structural applications. Looking ahead, further research is needed to refine our understanding of ductile fracture mechanisms. Future studies should focus on integrating advanced computational techniques, such as phase-field modeling and finite element analysis, to simulate crack propagation more accurately in complex composite structures. Additionally, exploring innovative material compositions and hybrid structures can provide valuable insights into enhancing ductility and overall fracture toughness. Moreover, the development of real-time monitoring technologies that assess stress and strain in composite structures during service could lead to proactive maintenance strategies, minimizing the risk of catastrophic failure.

Author contributions

Kiarash Irandoust: Investigation, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare no conflict of interest.

Data availability

No data is available.

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