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Fracture Mechanics Using COPRAS Method

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ABSTRACT

Fracture mechanics plays a key role in engineering by studying the behavior of materials with cracks and defects. It provides a scientific framework for predicting material failure in metals, polymers, ceramics, and composites. While Linear elastic fracture mechanics (LEFM) is useful for evaluating extended cracks, it faces challenges with shorter cracks and notches that require modifications such as the Griffith energy balance approach. Fracture mechanics is essential for studying high-cycle fatigue, brittle fracture, and crack propagation. Advances in finite element modeling and statistical evaluations of fracture toughness have improved predictive accuracy. Traditional techniques such as Linear Elastic Fracture Mechanics (LEFM) and Elastic-Plastic Fracture Mechanics (EPFM). serve as the foundation for assessing structural integrity. In addition, advances in finite element modeling and statistical fracture toughness analysis have greatly improved the accuracy of failure predictions. Result: Experimental evaluations, including tensile, fatigue, and fracture toughness tests, are essential to determine key parameters such as stress intensity factors and critical crack lengths. Numerical simulations, especially finite element analysis, provide accurate predictions of crack propagation and failure under various loading conditions. The results emphasize the important influence of material properties, crack orientation, and external forces on fracture behavior.

1. INTRODUCTION

The use of indentation fracture mechanics as a direct approach to assessing the mechanical properties of brittle materials has attracted much attention. Using fracture-mechanical and dimensional analysis, Evans and Charles Vickers independently studied surface radial cracks in brittle materials resulting from indentation [1]. In addition, coatings or paint layers are frequently applied to polymeric, metallic, or composite material surfaces for various purposes such as protection, decoration or improvement of surface properties. surfaces to perform a variety of functions, such as protection, aesthetics, barrier formation, or improvement of surface properties. When a coating deteriorates, it fails to fulfill its purpose, which can lead to system failure—not in a structural sense, but in terms of functionality. For example, a cracked paint layer compromises its visual appeal [2]. This review examines the basic principles of fracture mechanics from a theoretical standpoint. Given the extensive literature available in books, monographs, and journals, the field often suffers from content redundancy and the publication of findings that lack clarity for experts [3]. Fracture mechanics is an important tool for addressing various rock engineering challenges, such as rock shear, hydrocracking, explosive fracture, and rock stability. The application of Linear Elastic Fracture Mechanics (LEFM) to rocks is founded on Griffith's theory, which incorporates Irwin's modification, which highlights the importance of stress intensity near the crack tip. Irwin introduced stress intensity factors (SIFs) to describe the stress and displacement fields around a crack [4]. A key challenge in designing high-strength materials that

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resist fracture is that cracks significantly affect local stress distributions; a factor that traditional elastic stress analysis fails to address. Once a crack reaches a critical length, it propagates rapidly even under stress conditions below the material's static failure threshold. As a specialized branch within solid mechanics, fracture mechanics investigates the existence of cracks and quantifies the relationship between crack length, material resistance to crack growth, and stress conditions that trigger sudden fracture [5]. The Boundary Element Method (BEM) is recognized as a more accurate numerical approach, offering advantages over the Finite Element Method (FEM), especially in stress concentration analysis and problems involving infinite domains [6]. One of the main advantages of BEM is that it requires only boundary specifications rather than speculating the entire domain, which is computationally efficient. Conventional wood design methods based on stress or strain criteria are often inadequate in cases involving integrity [7]. The natural geometric properties and microstructure of wood introduce inherent peculiarities such as cracks, defects, and sharp corners, which traditional maximum stress-based approaches struggle to accurately predict [8]. Common structural challenges include drying cracks, notches, beam holes, dowel joints, and adhesive connections. In addition, knots and other irregularities in wood, acting as stress concentrators in the same way as cracks, further complicate load-bearing capacity assessments. These issues highlight the need for advanced fracture mechanics approaches in wood design. [9] When coated or painted structures experience short-term or long-term loading or are exposed to environmental factors such as temperature and humidity variations, cracks in the coating layer are often the first sign of failure is often the first sign of failure [10]. Although this does not usually result in structural failure, it can lead to functional degradation. Coatings serve a variety of purposes, including purposes such as aesthetic enhancement (paints), protective barriers (coatings), and electrical insulation [11]. The formation of cracks can reduce aesthetic appeal, compromise protective performance, or alter electrical properties. Therefore, predicting the conditions that cause coating failure and assessing the durability of coatings on different substrates is important in designing reliable coated structures. [12] This paper focuses on the challenges of calculating method combinations using numerical methods, particularly oscillating monoliths with the finite element method and virtual interlayer technology. It briefly outlines the mathematical principles behind monoliths, reviews current approaches to handling non-coherent strain energy release rate calculations, and explores new methods forpractical engineering applications. In addition, it presents case studies and proposes future research directions [13]. Linear Elastic Fracture Mechanics (LEFM) is very useful in predicting the behavior of cracked structures, especially in assessing brittle fracture and fatigue strength. In this regard, brittle fracture is characterized by failure resulting from crack propagation under increasing load, whereas fatigue refers to the progressive growth of cracks due to cyclic loading [14]. However, LEFM has some limitations, especially when analyzing short cracks and notches. Short cracks, defined as those below a certain critical length, often exhibit lower fracture strength than LEFM predictions and grow faster under fatigue loading than expected [15]. Railway sleepers are essential components in railway systems as they help distribute train axle loads to the supporting infrastructure. Initially, basic concrete sleepers were developed; however, traditional concrete sleepers did not meet industry requirements due to insufficient concrete quality and low tensile strength [16]. To address these issues, high-strength and pre-stressed concrete sleepers were developed, providing improved durability and performance. These advanced sleepers have gained widespread adoption worldwide, including in Iran. In Iran's railway network, monoblock pre-stressed concrete sleepers, especially the B70 model, are widely used due to their excellent strength and numerous advantages [17]. Their improved load-bearing capacity and resilience make them the preferred choice for ensuring stability and long-term reliability in railway infrastructure. The development and implementation of high-performance sleepers has significantly improved railway safety and performance, reinforcing their importance in modern transportation systems [18]. For the past five decades, fracture mechanics has been a major research focus in engineering, initially attracting attention due to catastrophic failures resulting from crack propagation. More recently, the emphasis has shifted to assessing internal damage in engineering materials to improve the long-term safety and reliability of structures and machines [19]. A fundamental aspect of fracture mechanics is the determination of the stress intensity factor (SIF) is widely recognized as the most reliable parameter for assessing crack propagation. Accurate SIF determination is essential to predict structural integrity and prevent unexpected failures, making it a key tool in material evaluation and engineering design [20].

2. MATERIALS AND MATHODS

Fracture mechanics materials cover a diverse range, including metals, polymers, ceramics, and composites each with unique fracture properties. Metals typically experience ductile fracture, where significant plastic deformation occurs before failure, whereas ceramics and glass undergo brittle fracture. Polymers can exhibit either brittle or ductile fracture, depending on factors such as temperature and strain rate. Composite materials are widely used in the aerospace and automotive sectors, display complex fracture behavior due to their heterogeneity.

Alternatives:

- **Specimen :** The capital letter A1 refers to the range of structures built in the 19th and 20th centuries. Three-point bending tests were performed in accordance with the RILEM guidelines for concrete, using an MTS machine with a maximum load of 20 kN.
- **Specimen :** The capital letter B1 refers to various structures built in the 19th and 20th centuries. Three-point bending tests were conducted continuously RILEM recommendations for concrete, using an MTS machine with a maximum load of 20 kN.
- **Specimen :** The capital letter C1 represents a range of structures built in the 19th and 20th centuries. Three-point bending tests were performed in accordance with the RILEM guidelines for concrete, using an MTS machine with a maximum load of 20 kN.

Evolution Parameter:

- **Notch Thickness:** In fracture mechanics, the peak thickness affects stress concentration, The onset and progression of cracks play a key role determining material toughness and fracture behavior, contributing to the assessment of structural integrity.
- **Density:** Density affects the mechanical properties of a material, affecting crack propagation, energy absorption, and fracture behavior. It is important in assessing structural performance and resistance to failure.
- **Young's Modulus:** In fracture mechanics, Young's modulus affects the stress distribution near a crack tip. Materials with a high modulus experience minimal deformation but are more susceptible to brittle fracture, whereas those with a low modulus can absorb more energy before breaking. The relationship between Young's modulus and fracture parameters, Stress intensity factor (SIF) and critical fracture toughness essential for predicting failure behavior and assessing structural integrity.
- **Tensile Strength:** Fracture mechanics approaches such as linear elastic fracture mechanics (LEFM) and elastic-plastic fracture mechanics (EPFM), use tensile strength to estimate material behavior under stress. The relationship between tensile strength and key parameters such as stress intensity factor (SIF) and fracture toughness is essential for predicting failure.

3. COPRAS METHOD

Despite advances in net-shaped FRP composites, machining remains an important finishing process for achieving complex geometries and precise dimensional and functional requirements. It plays a key role in shaping FRP composites into their final shape before assembly. Traditional Techniques such as band saw cutting often lead to subpar cut quality and reduce overall productivity. [1] Today, traditional materials are increasingly being replaced by advanced alternatives that offer reduced weight and improved performance. [2] Although glass and windows make up only a small portion of a vehicle's total weight and cost, they are essential for driver safety. Because of their importance, regulations establish minimum compliance standards for specific windshield properties. [3] Once considered a luxury, air conditioning has become essential for maintaining a comfortable living and working environment. It works by extracting heat and humidity from indoor spaces while cooling and circulating air. When choosing an air conditioner.[4] With the increasing demand for high-performance

materials in aerospace, energy, and chemical engineering, titanium alloys have emerged as a preferred choice for critical components. Their excellent high-temperature resistance, excellent corrosion protection, and impressive strength-to-weight ratio make them highly desirable [5]. However, conventional manufacturing techniques can be challenging to implement or expensive to manufacture. Disorders such as spinal cord injuries, cerebral palsy, multiple sclerosis, and muscular dystrophy. can cause muscle weakness, restricted movement, and coordination challenges. [6] Selecting the right cutting tool material for a machining operation offers many benefits, such as improved productivity, improved quality, superior surface finish, and cost efficiency. [7] Coconut husk fibers are obtained from the fibrous layer surrounding the inner brittle shell of the coconut fruit [8].These fibers are a by-product of the coconut fiber extraction process [9]. In many rural areas, they are often burned, leading to environmental concerns, especially in developing countries. Improving safety and crashworthiness in aerospace and vehicle systems has become increasingly complex with advances in transportation and aerospace engineering. [10]

4. ANALYSIS AND DISCUSSION

TABLE 1. Fracture Mechanics

Alternatives	Notch Thickness	Density	Young Modulus	Tensile Strength
Specimen	0.1	1718	1900	2.2
Specimen	0.1	1750	1880	1.5
Specimen	0.1	1809	4900	10

Table 1 shows the compares the mechanical properties of three samples, A1, B1, and C1, based on notch thickness, density, Young's modulus, and tensile strength. All samples maintain a uniform notch thickness of 0.1 mm, ensuring consistent testing conditions. Their densities range from 1718 to 1809 kg/m^3, reflecting variations in material composition. C1 demonstrates the highest Young's modulus (4900 MPa) and tensile strength (10 MPa), indicating superior stiffness and load-bearing capacity. A1 exhibits moderate performance, with a tensile strength of 2.2 MPa, while B1 records the lowest strength at 1.5 MPa, C1 shows the best mechanical performance among the three samples.

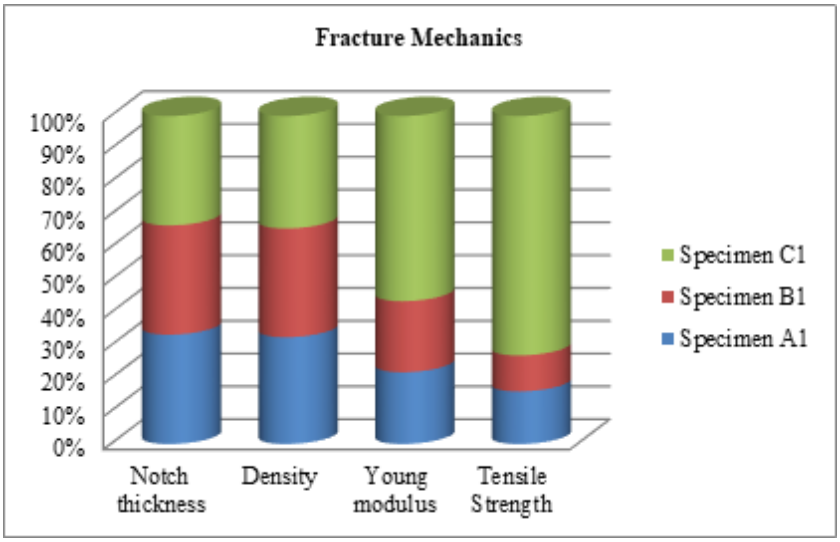


FIGURE 1. Fracture Mechanics

Figure 1 shows the stacked bar chart provides a comparative analysis of the mechanical properties - notch thickness, density, Young's modulus and tensile strength - of three samples: A1, B1 and C1. Each bar is divided to show the proportional contributions of sample A1 (blue), sample B1 (orange) and sample C1 (gray). Significant variations are observed, with sample C1 exhibiting the highest values for Young's modulus and tensile strength, while A1 and B1 contribute relatively little to the other properties. This visualization effectively highlights the differences in mechanical performance between the samples.

TABLE 2. Normalized Data

Alternatives	Notch Thickness	Density	Young Modulus	Tensile Strength
Specimen	0.333333333	0.3255638	0.218894	0.160583942
Specimen	0.333333333	0.3316278	0.21659	0.109489051
Specimen	0.333333333	0.3428084	0.564516	0.729927007

Table 2 shows the compares the normalized mechanical properties of samples A1, B1, and C1, considering notch thickness, density, Young's modulus, and tensile strength. All samples have an identical notch thickness value of 0.333, ensuring uniformity in crack propagation assessment. Density values show minor variations, ranging from 0.3256 for A1 to 0.3428 for C1. Regarding stiffness, C1 records the highest Young's modulus (0.5645), whereas A1 and B1 exhibit lower values of 0.2189 and 0.2165, respectively. Similarly, C1 achieves the maximum tensile strength (0.7299), followed by A1 (0.1606) and B1 (0.1095). C1 demonstrates superior mechanical performance.

TABLE 3. Normalized Data

Alternatives	Notch Thickness	Density	Young Modulus	Tensile Strength
Specimen	0.333333333	0.3255638	0.218894	0.160583942
Specimen	0.333333333	0.3316278	0.21659	0.109489051
Specimen	0.333333333	0.3428084	0.564516	0.729927007

Table 3 shows the weight distribution that is equally distributed among the three samples, A1, B1, and C1, of the four parameters evaluated. Each sample is assigned a uniform weight of 0.25 per parameter, ensuring an equal contribution to the overall evaluation. This approach implies that no particular property is given priority over others, enabling a fair and unbiased comparison of the mechanical properties of the samples. Such an equal weighting strategy is beneficial in decision-making situations where all factors are considered equally important in material selection and performance analysis.

TABLE 4. Weight Normalized Decision Matrix

Alternatives	Notch Thickness	Density	Young Modulus	Tensile Strength
Specimen	0.083333333	0.08139	0.054723502	0.040145985
Specimen	0.083333333	0.08291	0.054147465	0.027372263
Specimen	0.083333333	0.0857	0.141129032	0.182481752

Table 4 shows the compares the mechanical properties of samples A1, B1, and C1 using notch thickness, density, Young's modulus, and tensile strength. All three samples exhibit an identical notch thickness value of 0.0833, providing consistent conditions for crack propagation analysis. Density values show slight differences, ranging from 0.0814 for A1 to 0.0857 for C1. C1 records the highest Young's modulus (0.1411), indicating greater stiffness, whereas A1 (0.0547) and B1 (0.0541) demonstrate lower stiffness. Similarly, C1 achieves the highest tensile strength (0.1825), followed by A1 (0.0401) and B1 (0.0274).

TABLE 5. Bi

Alternatives	Bi
Specimen	0.164724275
Specimen	0.166240288
Specimen	0.169035437

Table 5 shows the provides a comparative assessment of the Bi parameter in the three samples A1, B1 and C1. The values exhibit small variations, 0.1647 in A1, 0.1662 in B1 and 0.1690 in C1. The gradual increase in the Bi parameter from A1 to C1 indicates small differences in material properties or performance characteristics. The highest value observed in C1 indicates a slightly greater influence of this parameter compared to A1 and B1. This assessment highlights the subtle differences between the samples, which may play a role in determining their suitability for specific applications where the Bi parameter is an important factor.

TABLE 6. Ci

Alternatives	Ci
Specimen	0.094869
Specimen	0.08152
Specimen	0.323611

Table 6 shows the provides a comparative assessment of the Ci parameter for three models—A1, B1, and C1—revealing distinct differences in their values. The value of A1 is 0.0949, B1 is 0.0815, and C1 is 0.3236.Among them, C1 shows the highest Ci value, which is higher than both A1 and B1, indicating a significant difference in material properties or performance. On the other hand, B1 indicates a relatively small contribution of this parameter. These variations in Ci may affect the applicability of the models in different contexts, especially in situations where this parameter plays a key role in material selection and performance.

TABLE 7. Min(Ci)/Ci

Alternatives	Min(Ci)/Ci
Specimen	0.8592829
Specimen	1
Specimen	0.2519067

Table 7 shows the provides a comparative assessment of the Min (Ci)/Ci ratio of A1, B1 and C1 – providing insights into their relative performance based on the minimum Ci value. B1 holds the highest ratio at 1, establishing it as the reference point, followed by A1 at 0.8593, while C1 records the lowest ratio at 0.2519. With a ratio of 1, B1 acts as a benchmark, indicating that its Ci value is very much aligned with the minimum value. A1, with a slightly lower ratio, suggests comparable performance, whereas C1's significantly reduced ratio reflects a significant deviation from the reference. This assessment highlights the differences in the alignment of the models with the minimum Ci value.

Table 8 shows the provides a comparative assessment of the Qi parameter for three samples, A1, B1 and C1. B1 exhibits the highest Qi value at 0.4031, followed by A1 at 0.3682, while C1 has the lowest at 0.2287. Among the samples, B1 shows the best Qi performance, indicating a high efficiency or contribution associated with this parameter. A1 ranks moderately, showing balanced performance, whereas C1 reflects a low Qi value, indicating a relatively low impact. These variations in Qi can affect material selection and application, especially in applications where this parameter significantly affects material properties and overall performance.

TABLE 8. Qi

Alternatives	Qi
Specimen	0.368231
Specimen	0.403074
Specimen	0.228695

TABLE 9. Ui

Alternatives	Ui
Specimen	91.35579
Specimen	100
Specimen	56.73786

Table 9 shows the provides a comparative assessment of the Ui parameter for three models—A1, B1, and C1—highlighting the variations in their values. B1 has the highest Ui value of 100, followed by A1 at 91.36, while C1 records the lowest at 56.74. The significantly higher Ui value of B1 indicates better performance in this aspect, making it the most efficient of the three models. A1 performs well, although slightly below B1, which indicates somewhat lower performance. Conversely, C1 has the lowest Ui value, reflecting a significantly reduced impact in comparison. These variations in material selection and use, in particular, Ui will be important sectors where this parameter is a key factor in determining overall performance and efficiency.

TABLE 10. Rank

Alternatives	Rank
Specimen	2
Specimen	1
Specimen	3

Table 10 shows the provides a comparative ranking of the three models—A1, B1, and C1—based on their overall performance across various evaluated parameters. B1 takes first place (rank 1), indicating the highest performance or suitability, followed by A1 in second place, while C1 ranks third with a lower ranking. The ranking highlights B1 as the most optimal choice for applications where these parameters are important. A1 shows balanced but slightly inferior performance, while C1 shows lower comparative performance, with C1 ranking last among the three models.

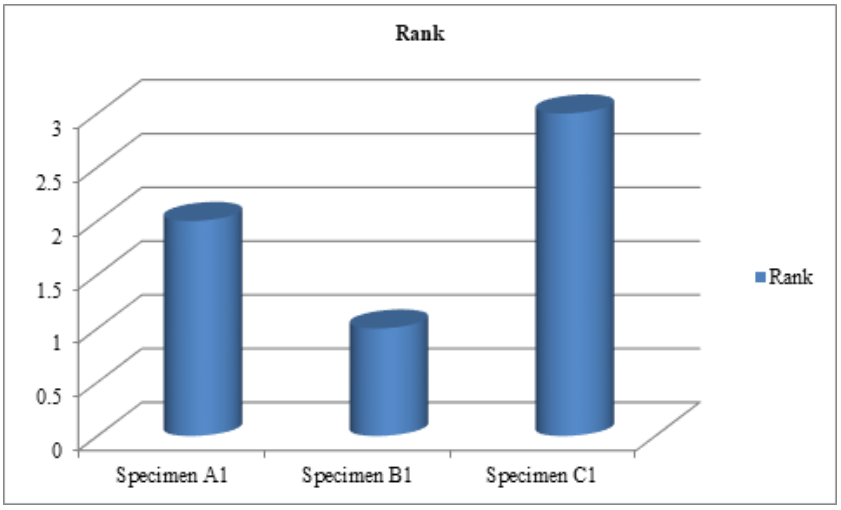


FIGURE 2. Rank

Figure 2 shows the provides a visual comparison of the rankings for three models—A1, B1, and C1—based on their overall performance across key parameters. The vertical axis represents the rank values, while the horizontal axis shows the model names. Among the models, B1 receives the highest rank (rank 1), indicating the best performance and suitability, followed by A1 in second place (rank 2). C1 has the lowest rank (rank 3), indicating relatively poor performance. This visualization effectively highlights the performance differences between the models, providing a clear and straightforward comparison. The rankings serve as a valuable reference in Making decisions easier by considering the evaluated criteria and selecting the most suitable model for specific applications

5. CONCLUSION

In cases such as cracking in fiber-reinforced materials, where traditional analytical solutions can be too complex, invariant integrals provide a more efficient and effective approach. A new boundary element method (BEM) approach, failure prediction method a method based on the maximum tensile stress criterion was designed to predict crack initiation direction and propagation paths in anisotropic rock discs under mixed-mode loading. BEM predictions for crack initiation angles and propagation paths demonstrated strong correlation with experimental results from previous studies on isotropic materials. In addition, Numerical simulations of crack initiation and propagation in CSTBD shale samples closely match experimental results, confirming the accuracy of the proposed method. The results indicate that the fracture toughness of anisotropic rocks is affected by both the intrinsic properties of the rock and the crack orientation. Although fracture mechanics is widely used in various engineering disciplines, its application in timber engineering remains largely a research focus rather than a standardized design method. Many existing timber engineering techniques rely on linear elastic stress analysis or empirical equations. The approaches discussed in these paper present significant advantages over conventional methods, providing improved accuracy and reliability in fracture analysis. Fracture mechanics provides a well-established and scientifically validated framework for deriving practical design formulations. Experimental findings for samples with PC or steel substrates show a reasonable correlation with the predicted fracture mechanics models. However, systematic deviations were noted, especially at low crack densities, as the crack density increases was slower than expected. Although these discrepancies may suggest potential errors in the fracture mechanics analysis, they reflect true variations in coating properties rather than errors in the analytical approach. Fracture toughness can be considered as a statistical parameter, variations of which lead to deviations between experimental results and theoretical predictions based on a single value. As the crack density increases, the impact of these statistical variations decreases, resulting in a closer alignment between experimental data and theoretical expectations. The strength of structures with narrow cracks and notches cannot generally be predicted using linear elastic fracture mechanics (LEFM).

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