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# Fracture Toughness of Composite Materials

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**Abstract:** ***The main conception of materials fracture in homogeneous, isotropic and composite materials is discussed. Important relations related to the linear elastic fracture mechanics are presented based on the Griffith-Irwin approach. Overview of composite failure modes and some facts about the fracture toughness was discussed next. Some testing methods for fracture toughness of composites are then compared, studied and analyzed. The composites materials which used in this test are ceramic composites such as Duceram, Duceram LFC, Sintagon Zx and Carrara Vincent. Three fracture toughness testing methods were involved in this experiment are the indentation strength method (IS), the single edge notched beam (SENB) and the Chevron notched beam method (CN). Finally, A revision of a new method for testing the fracture toughness was proposed. A Conclusion and recommendations for future work on fracture of structural composites was done.***

**Keywords:** Fracture toughness, material, composite, failure, fracture test**.**

## 1. Introduction

In material science, fracture toughness could be a property that describes the capability of a material which contains a crack to resist break, and is one amongst the necessary properties of any material for several design applications. The linear-elastic fracture toughness of a material is established from the stress intensity factor (k) at the moment which a small crack in the material starts to grow. It's indicated KIc and has the units of $pa\sqrt{m}$ or $psi\sqrt{in}$ . Plastic-elastic fracture toughness is indicated JIc, with the unit of J/cm2 or lbf-in/in2.

Fracture toughness may be an approach of express a material's resistance to brittle fracture when a break is happens. If the material has a high value of fracture toughness it'll most likely endure ductile fracture. Brittle fracture is incredibly characterize of materials with has a low fracture toughness [1].

Fractures have been happening for years ago, even at stress standards is beneath the yield strength. Continuing of such brittle failures (in vessels, ships and crafts) was occurred with a high percentage as the yield strength of component is getting higher. As a result, the engineering society must be careful about the study of the fracture problems which may be appears in any design application.

This shows that, most composite materials can offers a higher material strength compared to the conventional isotropic materials, for a liter weight. The recent aerospace requirements for high-performance hardware prove that. Thus, Composite materials are on their way to be the most desirable material in the aerospace industry. The purpose of this literature review study is to obtain a real understanding of the original sin of fracture of composite. Developing an analytical method for determine the fracture toughness is the conclusive target of this work as well as the flaws propagation characteristics of structural composites intended for design and construction applications. It is wished that this work and its following program will lead to future understanding of advance composite materials.

## 2. Literature review

### 2.1 Fundamental Concepts of Fracture Mechanics

The original Griffith theory [2] saying that an exist of a flaw (crack) will increasing and propagate in a disastrous way if the available elastic strain energy releasing rate exceed the increase in the surface energy of the flaw (crack). Thus, the existing flaw propagation will increase if the full energy of the system is decreased. He stated that "the general conclusion may be drawn that the weakness of isotropic solids, as ordinarily met with, is due to the presence of discontinuities, or flaws, as they may be more correctly called, whose ruling dimensions are large compared with molecular distances. The effective strength of technical materials might increase ten or twenty times at least if these flaws can be eliminated." His concept gave a real meaning for determine the true relation between fracture strength and the size of the crack in a brittle material. And so on, he ignores the work in plastic distortion which is thought to appear in or near to the flaw tip. Many authors have been giving profitable discussions on the effect of ignoring the plasticity. [2], [3].

In 1955, Irwin indicated that the energy approach is equivalent to a stress-intensity approach according to which fracture occurs when a critical stress distribution, characteristic of the material, is reached. An excellent account of the review on the equivalence of these two approaches is given by Paris and Sih. [3].

### 2.2 Fundamental Concepts of Fracture Mechanics

For convenience, the following sketch (figure 2.1) will be used in the present discussion concerning the basic mathematical relationships in fracture mechanics originally intended for homogenous isotropic materials.


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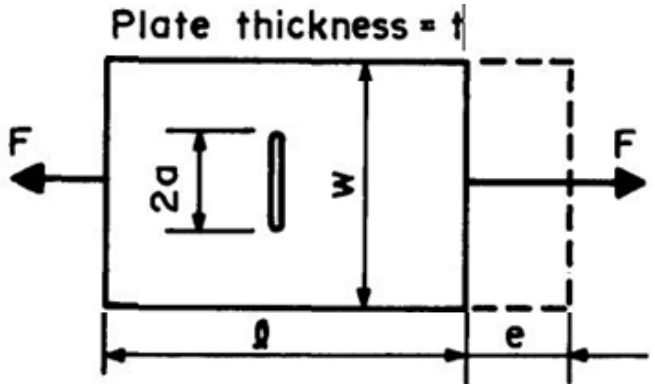


**Figure 2.1:** Testing plate

The plate shown above has a crack with a lateral dimension 2a, a unit thickness t, the loading is F1 and the elongation is equal to e. Three modes of crack propagation are known. They are shown on figure 2.2:

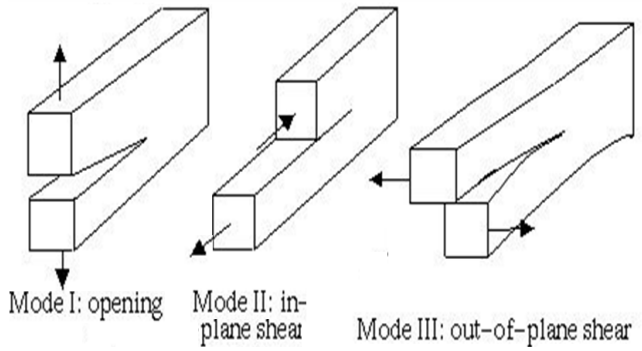


**Figure 2.2:** The modes of crack propagation

The opening mode is the crack propagation mode which related with the fracture toughness , so is known as Gic . In general, mode1,2 and 3 values for any materials have no similarity to each other. They should be resolute experimentally. In practice, Most people interest in Gic. As declared earlier, Irwin and others have given away that the failure performance of the materials sometimes is considered by the use of the stress intensity factor, K. The stress intensity factor is unlike the one which named stress concentration factors, even though there are some similarities. [4], For the plane stress situation, same as the plate considered earlier,

$$K_{Ic} = \sigma_f \sqrt{a} \quad (1)$$

Where, $\sigma f$ is the nominal stress based on the gross area of the plate.

The relation between the fracture toughness, Glc' and the stress intensity factor, K, heve been established, [23, 3]. For plane stress:

$$G_{Ic} = \frac{K_{Ic}^2}{E} \quad (2)$$

Where E is the modulus of elasticity of the materials. In the situation of plane strain, the corresponding equations are:

$$K_{Ic} = \sigma_f \sqrt{\pi a}$$

$$G_{Ic} = \frac{(1-\nu^2)}{E} K_{Ic}^2 \quad (3)$$

It should be noted that values for K for various cases with different combinations of loads and geometry can be found in several references [23, 10, 3, and 11]. The G value can be calculated using a laboratory tests by load an appropriate specimen, as pronounced previously. In the same time K value also can be calculated using the testing methods. Additional specifics will be known in the coming sections.

### 2.3 Some Facts about Fracture Toughness

It has been well-known that the conventional material's fracture toughness can be expressed in terms of either G or K. Nevertheless, Some facts which have useful values will be discussed in the coming points.

#### 2.3.1 Fracture Toughness and Fatigue

Cracks consistently occur in most of the materials for engineering causes. In the cases of repetitive loads, these cracks are growing in the sizes. In the end, these kinds of crack propagation lead to a total failure of the part. Hence, the machine's fatigue life of any element can be closely linked to the fracture toughness of the material. A full discussions has been dene by several journalists. [12, 2, 8].

#### 2.3.2 Fracture Toughness and Tensile Strength

As a material property, the fracture toughness differs from one material to any other. It is also differs from a grade of the material to any other grade of the same material. This information is evidently demonstrated in the next sketch (figure 2.3) [8]. An alike conclusion was written in a journal paper by Wei [13].

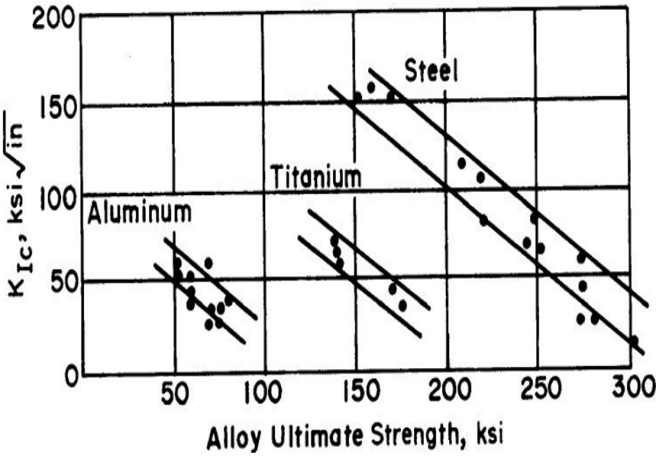


**Figure 2.3:** Alloy ultimate strength vs. Kic

### 2.4 The General Behavior of Composites

It is well-known that classic composite materials are made of a high strength fiber set in a connected matrix. It has quite low strength. The mechanical actions of the composites reasonably depend on the consistent performance of the element materials. For example the graphite epoxy composites have been found in a different even from the boron-epoxy composites. Meanwhile there are various fibers such as glass, graphite, boron, steel, etc. and also a quantity of matrix material presented nowadays, many mixtures can be done. Therefore, it has been supposed that the study the


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performance of certain composites on individual basis is important. The result which achieved in such way may be of engineering value. Unfortunately the testing result is uncommon even with the most composites underneath active study. This condition is mostly correct in the study of composite fracture. For that reason, in this study, it is important to refer to a testing record from several types of composite materials. By way of an outcome, the comments as well as conclusion which are made in this study are slightly general, maybe very common to be taken of a value from any other application. Comprehensive conferences on the mechanical properties for several composite materials will be found in some books [10, 11, 12, 13, and 14].

### 2.5 Overview of composite failure modes

For a specified loading condition, formation and propagation of damage within a laminate (its fracture toughness) will be lay-up dependent. Ultimately, failure will be governed by any one, or a combination of the ply level failure mechanisms illustrated in Figure 5.1. The failure modes which can arise through direct in-plane loading are:

#### 2.5.1 Translaminar fibre tensile failure

Although the critical strain energy release rate of a single carbon fibre has been estimated to be as low as 7.4 J/m2 [15], this mode of failure within a composite is characterized by the dissipation of large amounts of strain energy. The large amounts of fibre-matrix deboning and subsequent fibre pull-out, visible on the fracture surface shown in Figure 5.2(a), result in a homogenized ply-level fracture toughness that has been measured to be over 3 orders of magnitude higher than that of the fibre alone.

#### 2.5.2 Translaminar fibre compressive failure

Under an applied compressive load, failure of the fibres aligned with the loading axis can initiate as either shear driven fibre failure, Figure 5.2(b), or fibre kinking, Figure 5.2(c). Which failure mode occurs is dependent on the presence of shear stresses that can arise through features such as localised fibre misalignment. The relative motion of the crack faces during shear failure induces bending ahead of the crack tip, subsequently a transition to fibre kinking failure will always occur [16].

#### 2.5.3 Intralaminar matrix failure

This is characterised by matrix cracking either longitudinally or transversely with respect to the fibres, as shown in Figure 5.1. The fracture surface resulting from longitudinal intralaminar matrix failure is highlighted as in Figure 5.2(a). The measured toughness's of these failure modes are comparable to their interlaminar counterparts [17]. The critical strain energy release rates associated with these modes of failure are properties that are intrinsic to the material system, and need to be measured for complete characterization of the damage tolerance of the material system in question.

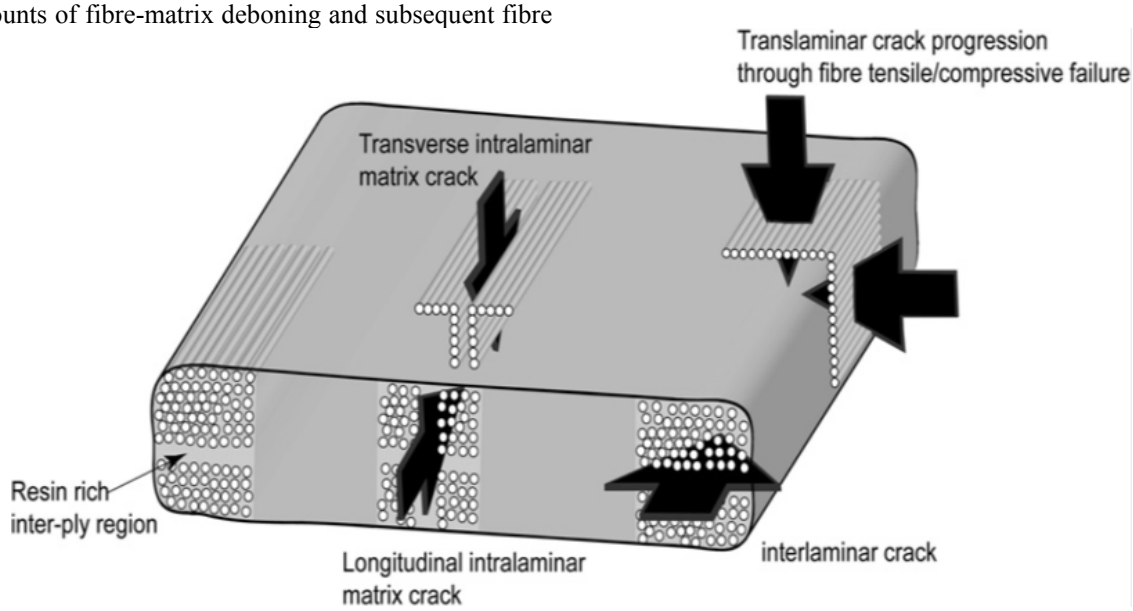


**Figure 5.1:** Overview of ply-level failure modes

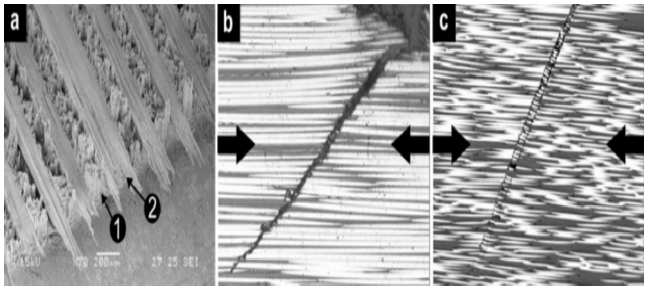


**Figure 5.2:** Failure mechanisms in FRP: (a) fracture surface including 1) translaminar fibre tensile failure and 2) Longitudinal matrix failure, (b) shear driven fibre compressive failure (the arrows indicate the loading direction), (c) fibre kinking (the arrows indicate the loading direction).

### 2.6 Fracture toughness testing of composites

The need of coming out with an effective design, together with the increasing of understand the concept of composites failure, all of this is taking the industry towards increasing of damage tolerant approach to plan with composites. Methods for expecting the starting and ending propagation of damage in composites components are much desired. Many ways are


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there to typical damage propagation, like using coherent element, X-FEM or smeared crack models [18]. Every one of those needs the fracture toughness of the failure mode which they simulate. That's why Improvement of experiment skills for perfect classification of the fracture toughness is, important.

Failure modes which been presented by coated composite is divided into, translaminar and intralaminar and delamination fracture. For many years, delamination was been in widespread research and studies. Round robin exercise [19] have prepared the path to the standardizing processes for the measure of fracture toughness mode I and mode II and mix mode I/II. Over the past years, the condition of the fine art of the interlaminar fracture toughness test method was widely studied by many writers [20].

Translaminar fracture toughness measurements have been dedicated to a considerable amount of published journals; nevertheless, these are usually special part of work with some dating back to the late 70's. While several years back the meaning of translaminar fracture toughness measurement was known, it was receive quite little attention from the scientific society till nowadays. That was mainly because of (1) the absence of confidence in composite leading to prohibited them from being used in prime constructions where it is useful to be used, and (2) the absence of modeling skills, which use the parameters in effective way.

Nowadays things have been changed: composite prime structure is widely used on the modern aircrafts, and a new tool has been commonly used in the design applications, which is finite element analysis (FEA). It is visualized that over the coming years, the fracture toughness related with the translaminar fracture modes will play more and more significant roles; therefore a review of the current literature is now opportune. This review show both, the conclusions of these study, and it is presents a discussion to help and make sure that further work in the field can be improved.

### 2.7 Test and Analytical Predictions

It has been well established that G'Ic , or K'Ic , is a material property, just as Poisson's ratio, the yield stress and the ultimate strength are. The latter ones are ordinarily determined by mechanical tests in a laboratory, by either the user or the material manufacturer. Therefore, it is quite logical that fracture toughness values, for a filamentary composite material being considered in a part design, should be obtained by reliable experimental method.

Alternately, the designer can resort to analytical methods in predicting the G (or K ) by using a few formulas and the basic material constants which characterize the behavior of individual constituent materials involved. As an example, he may use the following equations:

$$G_{Ic} = d\ (1-V_f)^2 \sigma_m \varepsilon_m / V_f \quad (4)$$

For unidirectional composites with non-metallic filaments in tough resin or metal matrices, such as the boron-aluminum or the glass-epoxy. To obtain the fracture toughness, the basic data needed are fiber diameter, volume fraction, the ultimate strength of the matrix, and the uniform elongation of the matrix.

### 2.8 Analyze and comparing some testing methods for fracture toughness of composite materials

Three fracture toughness testing methods were involved in this experiment:, the indentation strength method (IS), the single edge notched beam (SENB) and relatively suitable ASTM standard for ceramics, which is seldom used in dental ceramic studies, this method is the Chevron notched beam method (CN). Duceram, Duceram LFC, Sintagon Zx and Carrara Vincent were selected for the experiment. The specimens were checked for 10 measurements at least for one testing method. The test configuration is listed in table 8.1[21].

**Table 8.1:** The test configuration

| $K_{Ic}$ test method | CN | SENB | IS |
|---|---|---|---|
| Pre-crack processing | sawed notch | sawed notch | Vickers' indentation |
| Pre-crack type | growing crack | large crack (notch) | radial cracks from indentation |
| Fracture plane | Chevron triangle | half section rectangle | whole section rectangle |
| Proportions (B:W:S) | 2:3:12 | 1:2:8 | 2:3:22 |
| Dimensions (BxWxL) | 3 x4.5 x26 mm | 3 x6 x26 mm | 2 x3 x25 mm |

#### 2.8.1 Indentation strength method (IS)

In the central of the tensile faces of the beams, Vickers indentations were made at 19.6 N load. The radial crack which rise from the load, assist as the pre cracks in the experiment. Because the crack continue growing during the first little minutes following indentation, the beams were loaded after 20 to 30 min in a three point bending set up at 0.05 mm/min until fracture happened in a tensilometer. Specimens, where the fracture does not initiate from the Vickers indentation, were accepted from the study, and the test was continued until at minimum 10 satisfactory tests result was obtained. The fracture strength (σf) of specified specimens was calculated according to following formula:

$$\sigma_f = \frac{3FS}{2WB^2} \quad (5)$$

Where F is the fracture load; S the span length; W the specimen width; B is the Specimen thickness.

For every material, the elastic modulus (E) determined by a three point bending testing on beams without indentation (n = 10). The bending deflection (q) of the specimens loaded until failure is recorded. The modulus was calculated with:

$$E = \frac{FS^3}{4WB^3 l} \quad (6)$$


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The Vickers hardness (H) measured on damaged specimens (n = 10) using a 1.96 N load for 15 seconds, the magnitude of it prohibited the starting of the radial cracks. The hardness calculated with H = 1.854P/(2a)2, where P is the indentation load which equal to 1.96 N, and 2a is the magnitude of the two diagonals of the indentation. The facture toughness (KIc) obtained by calculation of this equation [22],

$$K_{Ic} = \eta(E/H)^{1/8}\left(\sigma_f P^{1/3}\right)^{3/4} \quad (7)$$

Where η is the geometrical constant (0.596), and P is the indentation load on the IS beams. The geometrical constant is slightly greater than the 0.59 used by Chantikul et al. [22], because they used 2 instead of 1.854 in the Vickers equation.

### 2.8.2 Chevron notched beam method (CN)

According to old study [21], a 0.1 mm diamond cutting was used to make a notch (Figure 8.2) with a Chevron angle θ of 60 ± 1.5° and a0/W ratio of 0.1 to 0.35. The beam was loaded in a three point bending testing. The variant of the CN was used, the maximum force Fm is used for the calculation and all the beams accepted, nevertheless of the load displacement plot, which were made at two samples per second. The Chevron notch length a0 and angle θ were measured at the two cracked sections of each specimen using optical microscopy (10×, measuring precision 1 µm). The toughness was calculated with the following equation:

$$K_{Ic} = \frac{F_m}{2W^{3/2}(1-\nu)^{1/2}\tan^{1/2}(\theta/2)} \cdot f(a_0/W)$$

$$f(a_0/W) = 17.959 + 20.708(a_0/W) + 179.53(a_0/W)^2 \quad (8)$$

Where S is the span; B the specimen width; W the specimen height; f(a0/W) the stress intensity shape factor; ν is the Poisson's ratio. The Poisson's ratio is 0.25 as recommended in ISO 6872 for biaxial flexural strength calculation.

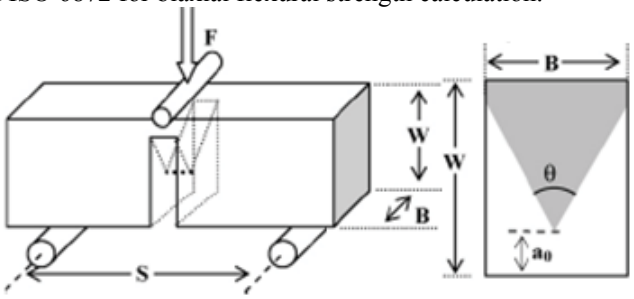


**Figure 8.2:** Chevron notched beam testing specimen

### 2.8.3 Single edge notched beam method (SENB)

The notches of the specimens were cut with a 0.1 mm diamond saw disc. The saw depth c was nearly half of the specimen's height W (Figure 8.3). The specimens were fractured in a three-point bending test. The two halves of the broken samples were used for the measurement of the notch depth c under an optical microscope. The length c was the average of the six values at three locations of the notch: in the middle and at two lateral sides of each section. The toughness value was calculated according to the following formula [24]:

$$K_{Ic} = \frac{F_c}{B} \cdot \frac{S}{W^{3/2}} \cdot f(c/W)$$

$$f(c/W) = 2.9(c/W)^{1/2} - 4.6(c/W)^{3/2} + 21.8(c/W)^{5/2} - 37.6(c/W)^{7/2} + 38.7(c/W)^{9/2} \quad (9)$$

Where Fc is the critical load; B the specimen width; S the supporting span; f(c/W) is the stress intensity shape factor.

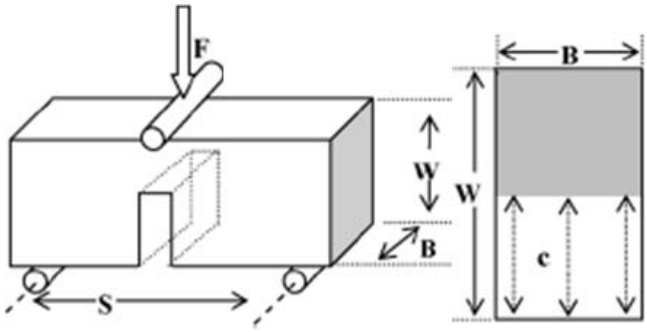


**Figure 8.3:** SENB testing specimen

### 2.8.4 Test result

The results are listed in table 8.4. The data variation coefficients (data scatter), calculated as the standard deviations divided by the means (in percent), were low and ranged from 3.6 to 10.2%


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**Table 8.5:** The test result

| Material | Mean fracture toughness ±SD and the data scatter in parentheses | | |
|---|---|---|---|
| | IS | CN | SENB |
| Duceram | 0.884±0.088 (10.0%) | 0.949±0.059 (6.2%) | 0.944±0.043 (4.6%) |
| Carrara Vincent | 0.809±0.053 (6.5%) | 0.843±0.062 (7.4%) | 0.882±0.032 (3.6%) |
| Sintagon ZX | 0.779±0.063 (8.1%) | 0.698±0.045 (6.4%) | 0.665±0.047 (7.1%) |
| Ducera LFC | 0.692±0.056 (8.0%) | 0.677±0.050 (7.4%) | 0.708±0.072 (10.2%) |

A total of three Duceram IS specimens were rejected because the fracture did not originate from the indentation, and extra beams were tested.

As indicated in table 8.6, SENB displayed statistical agreement with CN for all four dental porcelains tested in this study. IS was in agreement with CN for two materials, Duceram LFC and Carrara Vincent, and with SENB only with Duceram LFC.

**Table 8.6:** Pairwise comparisons of the method effect within material group

| Material | Method comparisons | | Difference(ns) | P |
|---|---|---|---|---|
| Duceram | IS vs | SENB | -0.060 | 0.020 |
| | | CN | -0.066 | 0.011 |
| | SENB vs | CN | (-0.006) | 0.823 |
| Carrara Vincent | IS vs | SENB | -0.073 | 0.005 |
| | | CN | (-0.034) | 0.187 |
| | SENB vs | CN | (0.039) | 0.128 |
| Sintagon Zx | IS vs | SENB | 0.114 | 0.000 |
| | | CN | 0.081 | 0.002 |
| | SENB vs | CN | (-0.033) | 0.194 |
| Ducera LFC | IS vs | SENB | (-0.016) | 0.525 |
| | | CN | (0.015) | 0.550 |
| | SENB vs | CN | (0.031) | 0.225 |

**2.9 A revision of a new method for testing the fracture toughness**

A new methodology known as the straight notched disk bending methodology is developed for mode I fracture toughness determination by rock cores. Disk specimen of andesite and marble having one straight edge notch were subjected to three point bending load. Dimensionless stress intensity issue estimations and fracture toughness tests were conducted for various notch lengths span lengths thickness and diameters of the cylindrical rock specimens Stress intensity factors were computed by three dimensional finite component modeling and also the results were conferred for a large vary of specimen geometrical parameter. Benefits of the new methodology enclosed straightforward specimen preparation and testing procedure, stiffer specimen pure mathematics, smaller fracture method zone, and suppleness of the specimen pure mathematics for the investigation of the scale impact behavior.

For cylindrical rock core specimens, common methods applying three-point bending to determine KIc include straight edge cracked round bar bend (SECRBB) method [25,26], semi- circular bending(SCB)method [27,28], chevron bend(CB)test [29], and chevron notched semi-circular bending method [30]. For Brazilian type compressive loading of rock disks, various methods were proposed for KIc determination. Cracked straight through Brazilian disk (CSTBD) method [31], diametric compression test [32], cracked chevron notched Brazilian disk (CCNBD) method [33], modified ring test [34], Brazilian disk test [35], flattened Brazilian disk method [36], and hole-cracked flattened Brazilian disk method [37] are some of the methods used for fracture testing of rock cores under compressive upper and lower boundary loads. Among these methods, CCNBD method is one of the suggested methods of ISRM [38] for fracture toughness testing on rocks. Some methods such as SCB and SECRBB with straightedge- notched specimen geometry [39–40] under three-point bending were reported to yield KIc values lower than the suggested methods by ISRM. Suggested methods by ISRM involve SR method [41, 29], CB test [29], and CCNBD method [38].

## 3. Conclusion and Recommendation

As an outcome of this part time revision off the fracture toughness of the composites materials, an insufficient number of points have become clearly understood. It seems that the filamentary composite materials like graphite-epoxy and boron-epoxy will be used in the applications of aerospace in increasing scales. This is because of the good mechanical properties that they have. Nevertheless, the fracture toughness of materials like this is not understood well. To cover the way to successful future applications, it is manipulated that a carefully planning efforts need to be done.

In this time of life of the up-to-date computers, computers should play a big role and be very useful in the theoretically investigations and study of the fracture toughness of composites. A limited new publication nowadays is working on computers which can numerically do the evaluation of the fracture toughness of conventional materials; it is appear to have placed a good basis for studying in the composite fracture areas.

Specimen geometries under three-point bending or four-point bending and related testing techniques are attractive for KIc determination due to the easiness of specimen


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preparation and simplicity of testing configurations. For comparison of fracture toughness test results, wide availability of results with these geometries and testing techniques is another advantage of these methods. For cylindrical rock core specimens, common methods applying three-point bending to determine KIc include straight edge cracked round bar bend (SECRBB) method [42] and [43], semi-circular bending (SCB) method [44] and [45], chevron bend (CB) test [46], and chevron notched semi-circular bending method [47].

Based on results of a limited number of tests, it was suggested that the linear elastic fracture mechanics based on the Griffith theory could be extended to the orthotropic materials of which the fiber composite material is one. At this time, most evidences available do support this suggestion, despite the question of heterogeneity of composites. Whether this tentative conclusion is also valid with the general filamentary composites remains to be seen.

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