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Fracture Toughness of Kenaf Mat Reinforced Polyester Composite

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ABSTRACT

The fracture behaviour represents the most critical issue in the automotive and aerospace engine fields. Thus, the objective of this study was to estimate and analyze the crack criteria by using the Mathematical laws that were limited in E 1820 standard and the results affirmed by applying the numerical solutions of ANSYS to estimate the fracture toughness value KIC, besides the energy release rate of biomass composite. The specimens were prepared from different percentage of kenaf mat (KM) and unsaturated polyester resin (UP) 20% KM – 80% UP and 40% KM – 60% UP, respectively, as well the other composite properties which were calculated using the stress-strain data. The fracture characterizations of this composite were carried out using the compact tension (CT) specimen that was commonly used to determine Mode-I fracture properties. The fracture toughness has been found to be independent of pre-crack length. Meanwhile, the tests were performed at room temperature. The numerical simulations of the ANSYS model results demonstrated a good agreement between the experiments computed results of the fracture toughness. The fracture toughness KIC of 20% KM – 80% UP and 40% KM – 60% UP was equivalent to 0.76 MPa√m and 2.0 MPa√m, respectively. Thus, the fracture propagation is dependent on the fibre percentage of the composite. On the other hand, there are unlimited mechanisms of crack paths derived from randomly kenaf mat packs, particularly in the frontal process zone of crack tip.

Keywords: Fibre, fracture toughness, energy release rate, kenaf mat composite, unsaturated polyester resin

NOMENCLATURE

Ao	original measured crack length
Ai	current crack length
Ao	Initial measured crack length
Δa	= a(i)-ao
KIC	Fracture toughness
KI	Stress intensity factor
J	J-integral
JIC	Energy release rate
JPL	Plastic component of J
Jel	Elastic component of J
B	Specimen thickness
BN	Net specimen thickness BN=B if no side grooves are present

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Be	Express as B-(B-BN)2/B
E	Young's modulus
N	Poisson's ratio
σY	Yield stress
Σel	Ultimate stress
KIC	Fracture toughness
KI	Stress intensity factor
JIC	Energy release rate
H	Initial half-span of the load points
R	Radius of rotation of the crack centreline
ϴ	Angle of rotation of a rigid body element about the unbroken midsection line
E	Young's modulus
ν	Poisson's ratio
σY	Yield stress
σel	Ultimate stress
KIC	Fracture toughness
KI	Stress intensity factor
JIC	Energy release rate
H	Initial half-span of the load points
R	Radius of rotation of the crack centerline
ϴ	Angle of rotation of a rigid body element about the unbroken midsection line

INTRODUCTION

The natural fibre composite reorganized exceptional benefits that were derived from the specific mechanical properties of the fibre and the adequate toughness that represents prerequisite issues of most engineering applications. Thus, the researchers' interest shifted to analyzing the fibre architecture effect at the toughness quantity (Maya and Sabu, 2008).

Liu and Hughes (2008) studied the toughness and fracture behaviour of the flax fibre woven reinforced epoxy resin. Hence, the results demonstrated the enhancement of composite resistance derived from the fibre distribution technique that controls the composite morphology by using regularly woven textiles. Thus, the random orientations of composite fibre lead to increasing the defects of the composites. Recently, numerous studies have been investigating on natural fibre reinforcement in polymeric composites. This fact is based on both fibres and matrixes that are derived from renewable resources. Thus, the formed composites have more compatibility with environmental preservation issues. In addition, biomass composites have recently gained extensive domination in the industrial field for their significant properties, such as renewal ability, degradable, density, high specific strength, being lightweight, as well as low cost and desired mechanical properties. Meanwhile, the plant fibres that originate from leaf or hard fibres, seed, fruit, wood, cereal straw and other grass fibres, whereby the cellulose fibrils embedded in lignin matrix. Liu and Hughes found an increase of fracture toughness in woven fabric and this improvement is most probably the result of an increase in the fibre volume fraction due to better packing of the fibres, rather than the woven textile. The fibre length and formation nature have influenced on the tensile strength, rigidity, fracture toughness, and flexural strengths values of the composites.

The polymers, such as elastomer, thermoplastic, thermosetting, rigid and flexible foams, represent the most essential substances entire of composites formation. The fibre-polyester composites are attractive due to their structural versatility which enables them to be used in the manufacture of load bearing composites (Farias *et al.*, 2008; Sharifah *et al.*, 2003). The natural fibres suffer a few limitations like low compatibility with the polymeric matrix because of their typical hydrophilic characteristic. However, some selected elements of the composites must be more compatible for natural fibres and resins due to ability of the hydroxyl groups that contain hydrogen bond between the fibre and polymer to represent a major role in directing the crystalline packing (Matthews and Rawlings, 1994). Many studies have notable success in determining the fracture toughness of K_{IC} determinations and J-integral (e.g. Rodney and John, 1999; Dvorak, 2000). The procedures employed in this study are similar to those applied to metals in ASTM E1820. A number of investigations on the fracture mechanism at the crack tip of the fibre composites have described the microstructure behaviour of these areas (Patricia *et al.*, 2002). All materials, which are either ductile or brittle, homogenous or composite, have defects and cracks, which contribute to more degradation. Generally, the microstructure of materials is studied to better understand the fracture behaviour of the materials precisely under any situation for a wider application (Sami and Ridha, 2005). At the same time, the environment also has significant effects in the fracture toughness mechanism and energy absorption amount of the composite materials (Dash and Chatterjee, 2004). One of the accepted methods of analyzing the fracture behaviour is the application of the Linear Elastic Fracture Mechanics (LEFM), whereby the attention is focused on exploring the fracture mechanism in the crack tip of the fibre composite.

Most of composite material applications are fabricated from brittle matrices and high modulus fibres. However, the stress intensity factor and energy observation rate can be estimated using the linear elastic fracture mechanic concepts. The main energy observation mechanism can be interpreted as crack deflections that are generated from the crashing of the polymer bonds between agglomerate fibres. Meanwhile, tilting paths or twisting motion around the fibres can be produced according to the fibre distribution and the pullout fibre (extraction of fibres from the matrix) and fibre-bridging mechanism kind of the one distinct failure mode of the randomly fibre as the spatially mat fibres. Thus, it can be stated that no limitation mechanism can dominate to estimate the fracture behaviour (Atodaria *et al.*, 1997). Kao (2003) studied the fracture toughness of a laminated composite, and affirmed that the energy required before the onset of fracture was unexpectedly large, i.e. around five times larger for the separate Al-foil layer. Other studies have been focused at estimating the microstructure fracture mechanism (Wong and Mai, 1998; Silva *et al.*, 2005) as attempts to study the limited stability of fracture mechanism.

Preparation of the Sample

The material subject in the present study was constructed from kenaf mat for its significant property advantages, such as low cost, and high filling levels that possibly resulting in high stiffness properties unlike brittle fibres. A comparison was done between the fracture toughness amounts for the different percentages of the kenaf mat reinforced and unsaturated polyester (UP) resin.

Generally, the composites that are fabricated from the fibre-reinforced polymer encountered dramatic improvement in both their tensile and flexural properties. Unsaturated polyesters are used for a variety of industrial and consumer applications. This investigation split into two major computation scopes to estimate the fracture toughness and energy release rate; these include the numerical analysis of ANSYS and the experiment data for 20% KM – 80% UP and 40% KM – 60% UP specimens. Meanwhile, the compact tension (CT) specimen was constructed according to the E1820 standard for the fracture toughness measurement. All the parameters of the specimens are illustrated in *Fig. 1*.

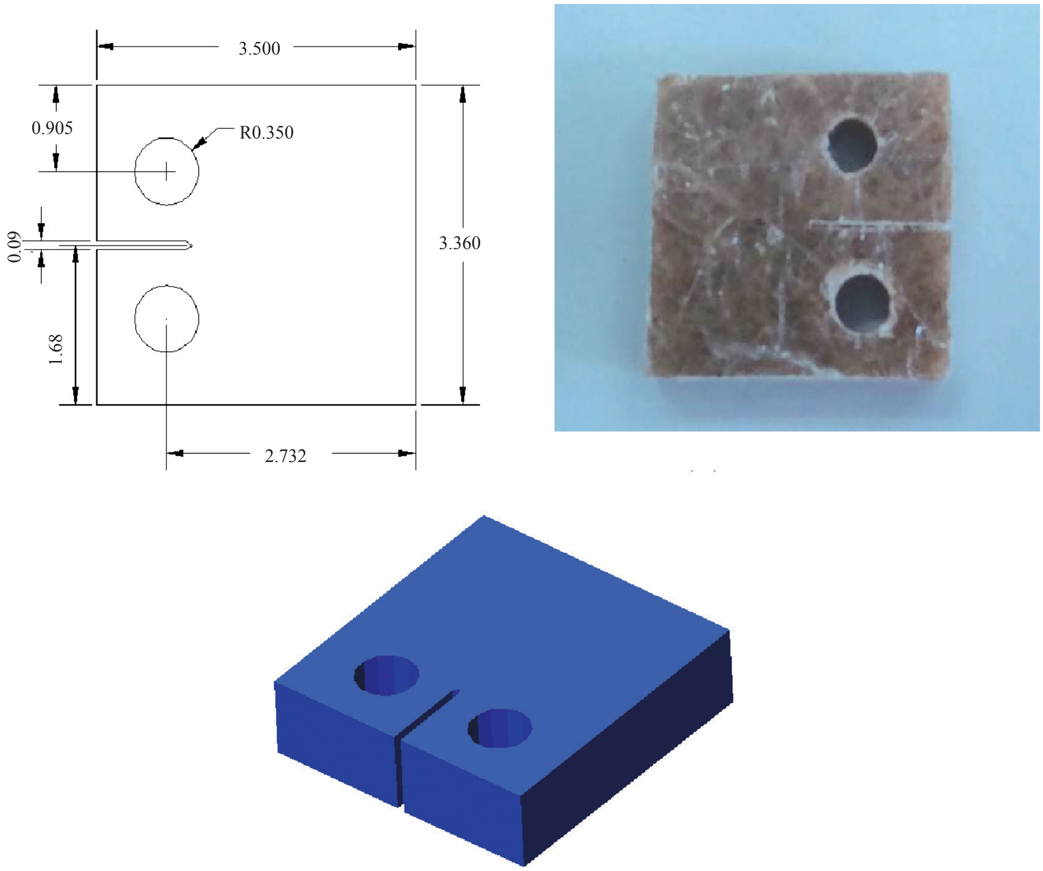


Fig. 1: (a) The front view of the CT specimen; (b) the compact tension specimen 20% KM -80% UP; and (c) Izo AutoCAD drawing of CT specimen

The thickness was 7 mm for all the specimens, while the initial notch length to specimen was between 12.6 mm and the notch tip was sharpened with a razor blade to simulate a sharp crack. The tensile test for 15 specimens was conducted to estimate the fracture toughness and J-integral for this particular composite. The tensile young modulus, yield load, and extension at yield point were calculated automatically.

Tensile Testing of Composites

The tensile specimen, i.e. 145 mm by 15 mm, was caught according to ASTM D3039 /D3039M-95M; the composite of the tensile specimen is as illustrated in *Fig. 2*. Testing was conducted and the data were digitally acquired. The tensile stress, tensile strain and young modulus of 20% KM – 80% UP and 40% KM – 60% UP were calculated automatically as indicated below. The young modulus for these composites was 4488 MPa and 4780 MPa, respectively. The test was performed in the instron machine 10 kN, series 2716 and 2736 under test speed that is limited by 2 mm/min. The specified test conditions for determining the tensile properties of specimen were conducted according to ISO 527.

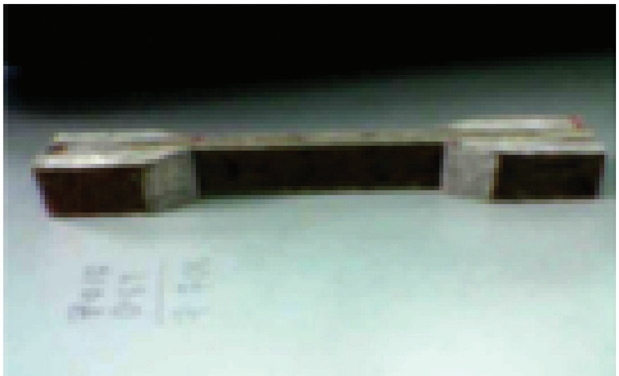


Fig. 2: ASTM D3039 tensile specimen

The tensile test was performed for fifteen compact specimens under stable speed rate to estimate the energy release rate and fracture toughness. Accurate evaluations were recorded for the limited the Poisson's ratio of the composite via recourse of the composite materials gage strain.

RESULTS AND DISCUSSIONS

The tensile results of 40% KM – 60% UP denote the dramatic improvement in the yield load of the composite which increase the fibre percentage. The tensile results are shown in Table 1, while the load-displacement graph is illustrated in *Fig. 3*.

TABLE 1
Tensile results of the kenaf–polyester composite

Kenaf–polyester percentage	Yield stress MPa	Young modulus Mpa	Tensile extension at yield point mm
20%KM – 80%PU	26.648	4488	1.836
40%KM – 60%PU	28.295	4780	1.6003

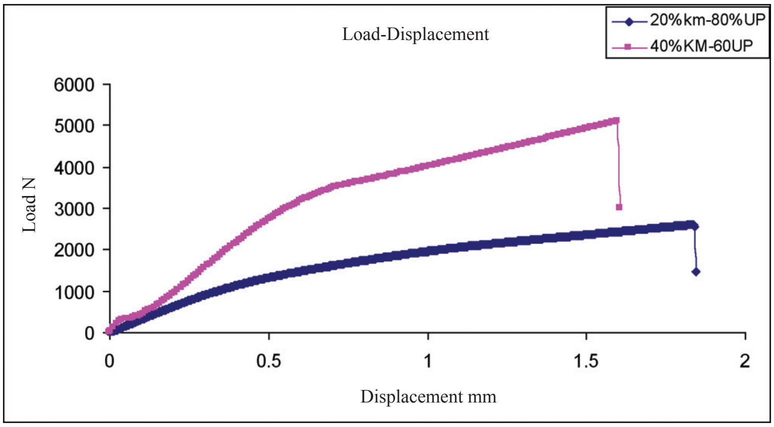


Fig. 3: The tensile load-displacement graph

The combat specimen was generally used only for the k_{IC} testing.˙ At load $P_{(i),}$ the calculation of K_i was computed instantaneous at all the recorded points in the load-displacements curve, as follows:

The current crack length was calculated from the knowledge the instantaneous load-displacement slope that was required to find $C_{c(i)}$, as follows:

$$slope = \left({}^{\Delta v}\!/_{\Delta p} \right)_i \tag{1}$$

with:

$$ {}^{ai}\!/_{w} = [1.000196 - 4.0631u + 11.242u^2 - 106.043u^3 + 464.335u^4 - 650.677u^5 \tag{2}$$

Hence:

$$u = \frac{1}{[B_e E C_{c(i)}]^{1/2} + 1} \tag{3}$$

Thus, the instantaneous fracture can be mathematically expressed using the following expression:

$$K_{(i)} = \frac{P_i}{(BB_N W)^{1/2}} f(a_i / W) \tag{4}$$

$$f(a_i / W) = \frac{[(2 + a_i / W)(0.886 + 4.64(a_i / W) - 13.32(a_i / W)^2 + 14.72(a_i / W)^3 - 5.6(a_i / W)^4)]}{(1 - a_i / W)^{3/2}} \tag{5}$$

Meanwhile, J for the compact specimen was calculated, as follows:

$$J=J_{el} + J_{pl} \tag{6}$$

The J calculations for the basic test method for the compact specimen are related to the Poisson's ratio and young modulus.

$$J = \frac{K^2(1 - v^2)}{E} + J_{Pl} \tag{7}$$

The plastic component of J was calculated, as follows:

$$J_{pl} = \frac{\eta A_{Pl}}{B_N b_o} \tag{8}$$

In order to account for the crack opening displacement, the crack length estimation shall be corrected for rotation, while the compliance is corrected, as follows:

$$C_{c(i)} = \frac{C_i}{[\frac{H}{R}\sin\theta_i - \cos\theta_i][\frac{D}{R}\sin\theta_i - \cos\theta_i]} \tag{9}$$

Where:

$$u = \frac{1}{[B_e E C_{c(i)}]^{0.5} + 1} \qquad (10)$$

In addition, the crack length is given as follows:

$$a_i / W = [1.000196 - 4.06319u + 11.242u^2 - 106.043u^3 + 464.335u^4 - 650.677u^5] \qquad (11)$$

The experimental results for the fracture toughness of 20% KM – 80% UP were equivalent to (0.95 MPa .√m) and in the 40% KM – 60 UP equal to (2 MPa. √m), this finding denoted the relationship between the fibre percentage and the increase in the fracture toughness value. The tolerance of K_{CL} value between the specimens is related with the fibre microdiameter or the kenaf picks diameters at the crack tip and the crack zone morphology, whereby no mechanism can dominate an accurate assessment for the fracture toughness of the mat composites. Thus, the K_{CL} releases, depending on the average of fracture toughness values to characterize the K_{CL} values of the composite, whereas in order to obtain more accurate calculations, the numerical analysis was performed to only the K_{CL} value.

TABLE 2
Experiments and numerical results for the fracture toughness and energy release rate

Specimen percentage contents	No. specimen	K_{Lc} experimental results MPa √m	Experiment energy release rate KJ/m^2	K_{Lc} numerical results MPa √ m	Numerical energy release rate KJ/m^2
20 KM-80UP	1	1.8899	0.716	1.515	0.465
	2	0.779	0.123	1.0406	0.219
	3	1.0287	0.214	0.9499	0.182
	4	0.855	0.148	0.8837	0.158
	5	1.6577	0.557	1.2877	0.336
	6	0.4319	0.037	0.787	0.125
	7	0.5046	0.051	0.922	0.172
	8	0.8405	0.143	1.058	0.226
	9	0.5546	0.062	0.785	0.124
average		0.95	0.182	1.025	0.213
40 KM-60UP	1	1.935	0.712	2.945	1.650
	2	1.452	0.401	2.185	0.908
	3	2.32	1.024	2.75	1.439
	4	2.14	0.871	2.5	1.189
	5	2.57	1.257	2.04	0.792
	6	1.36	0.352	2.593	1.279
average		2.0	0.761	2.49	1.180

The potential errors in the ANSYS module solutions were derived using homogenous material, while the experimental results dominate the heterogeneous of distribution and orientation of the fibre in the crack tip. *Fig. 4* illustrates the stress component that is concentrated at the yield point

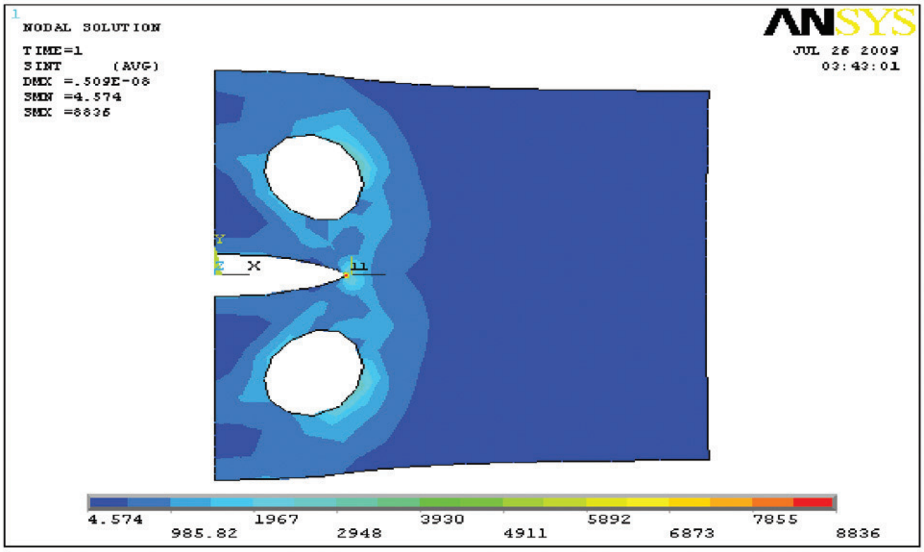


Fig. 4: The stress deformation of the simulation specimen

of the crack tip. Three deformation concentration zones were generated according to the forces compounds that influence the edges of the corresponding circular holes and crack tip. The plastic zone size in the crack tip, J_{max} and $\Delta a_{max,}$ could be estimated for the composite subject study, as illustrated in Table 3.

TABLE 3
The crack parameters and the maximum energy release

Composite percentages	r_p (m)	J_{max} (KJ/m^2)	$\Delta\ a_{max}$ (m)
20%KM- 80% UP	6.74×10^{-5}	9.327×10^{-3}	1.75×10^{-3}
40%KM – 60% UP	2.65×10^{-4}	1.27×10^{-2}	2.25×10^{-3}

The J-integral values and the corresponding crack extension values must be plotted, as shown in *Fig. 5*. Hence, the J-R curve is defined as the data in a bounded region by the coordinate axes, J_{max} and $\Delta\ a_{max}$, as illustrated in *Fig. 5*.

Particularly in the ANSYS programme, there is a complexity of construct in the composite model, whereby the content kenaf mat acts as randomly reinforced fibre. Thus, the material properties of the Young's modulus and poisson's ratio of the composite can be dominated by recourse the tensile test results. The results exhibit a good agreement with the findings of the experiment, as shown in *Fig. 6*.

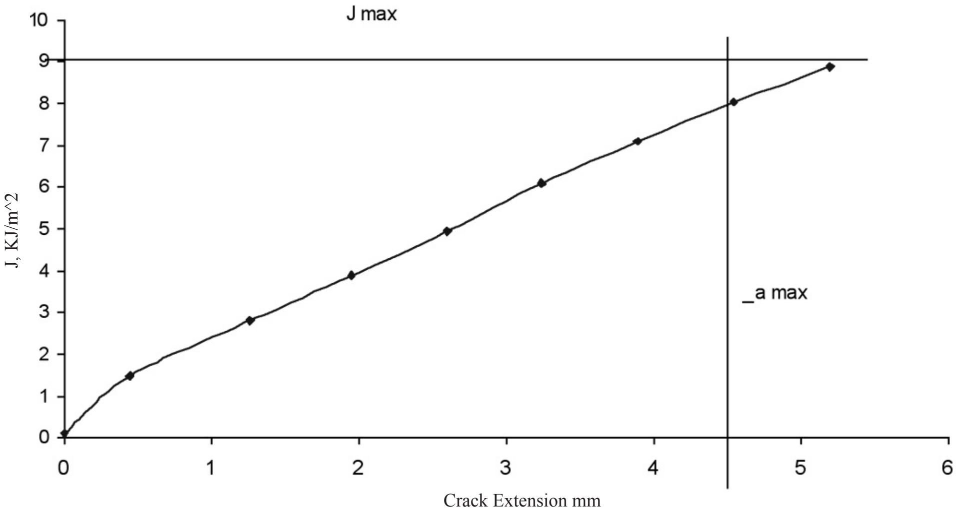
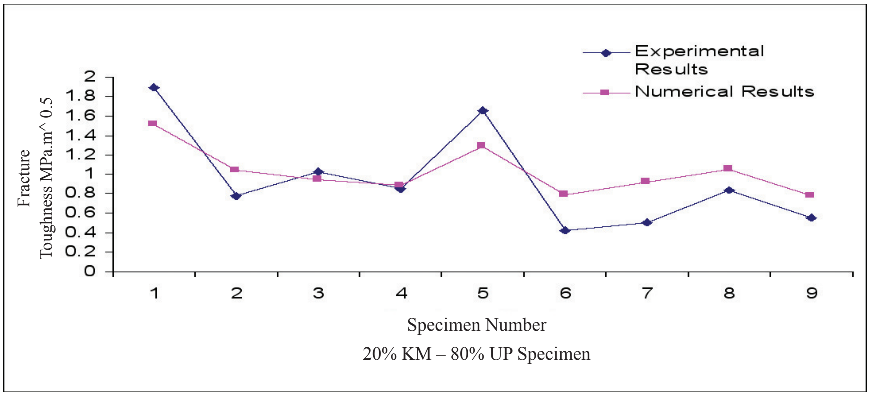


Fig. 5: Crack extension and energy release rate (J-R curve) of 20% KM – 80% UP



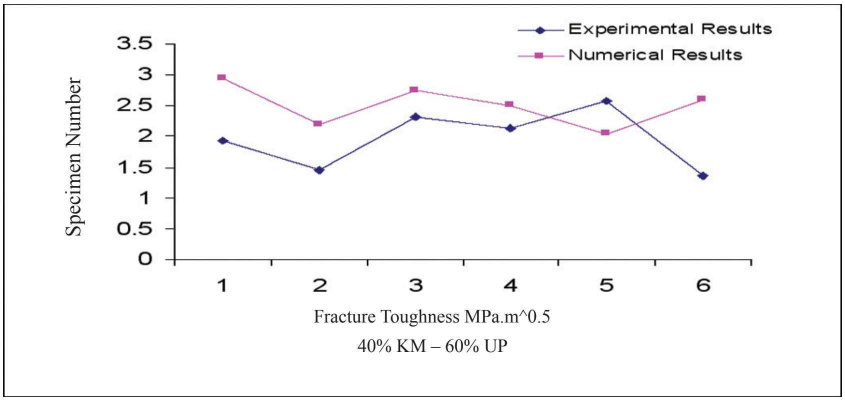


Fig. 6: The tolerances between experiment and the ANSYS results for (a) 20% KM – 80% UP and(b) 40% KM – 60% UP

CONCLUSIONS

From this investigation, a number of conclusions can be drawn, as listed below.

1. The tensile result of 40% KM – 60% UP demonstrated a dramatic improvement in the yield load of the composite with the increasing percentage of fibre.
2. Based on the experiment, the fracture toughness results of 20% KM – 80% UP were found to be equivalent to (0.95 MPa .√m) and this was equivalent to (2 MPa .√m) in the 40% KM – 60 UP, demonstrating the relationship between the fibre percentage and the increasing value of the fracture toughness.
3. The numerical results exhibited a good agreement with the results from the experiments.

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