Carbon/Epoxy Woven Composite Experimental and Numerical Simulation to Predict Tensile Performance

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***Abstract*-Currently, there is demand for the utilisation of woven composites in aerospace and industrial applications, mostly due to their superior strength-to-weight ratio and thermal properties, as opposed to conventional materials. However, the mechanical behaviour of woven composites is not on par with traditional materials. The central objective of this study is to develop an understanding of three-dimensional woven composites through the improvement of accurate numerical models that are also validated with experimental results. Five specimens were fabricated using American Society for Testing and Materials (ASTM D3039) guidelines to study the mechanical performance of carbon/epoxy. The experimental tensile tests results and the finite element analysis outcomes for the carbon/epoxy composite agree with each other, with 5.05 percentages of error, which validates the numerical results.**

Keywords- Composite Materials; Matrix Composite; Numerical Simulation

I. INTRODUCTION

Generally, the word composite means being constituted of multiple parts. In practice, the term composite material or composites are used in a more restrictive sense; a material constituting an assemblage of two or more materials with differing natures and complementary properties, leads to a material that possess superior properties to its original constituents. Composites are preferred due to several factors: two or more materials, combined on a macroscopic scale, form a very useful material [1-2]. Carbon fibres are one of the most advanced and promising engineering materials. It is relatively new, and therefore expensive, severely limiting its actual application. Nevertheless, it is host to a multitude of wondrous properties, such as high-tensile module and tensile strengths that are creep resistant, possessing high fracture toughness, low coefficient of thermal expansion, relatively high thermal conductivities, and low susceptibility to thermal shocks. However, it is not without weaknesses, chiefly among them is its propensity for high-temperature oxidation and electrical conductivity [1]. Carbons are most commonly used as reinforcements in advanced polymer-matrix composites [2] due to its many unique properties; it can be customised into many engineering applications. Carbon-reinforced composites are currently being utilised extensively in sports and recreational equipment (fishing rod, golf clubs), filament-wound rocket motor cases, pressure vessels, aircraft structural components, and both military and commercial aviation, such as fixed wing aircrafts and helicopters (e.g., as wing, body, stabiliser, and rudder components).

The matrix bonds the materials together into a single structural unit that protects them from external damage, while distributing the applied loads to the fibre, which in many cases, results in improvement of properties such as ductility and toughness. In a unidirectional material, a strong interface bond between the fibre and the matrix is required, especially for polymer composites, as the matrix must be capable of developing mechanical or chemical bonds with the fibres, or be able to do so via an interface. The fibre and its matrix should also be chemically compatible, especially in high temperature environments. The matrices also determine the level of moisture absorption, temperature limitations, and outgassing characteristics. For example, polyesters are most commonly used with fibreglass, due to the fact that they have excellent mechanical properties, are easily handled and moulded, and cost much lower than other matrices. If higher strength and chemical resistance are the structure's priority, then epoxy matrix should be used, but this comes at a cost. The resulting failure strength of a composite usually lies between the failure strength of the fibres and that of its matrix, with some fibres breaking at different times, while other fibres pulling out at points where the matrix-fibre adhesion fails. Due to the fact that the polymer matrix is responsible for the load transfer between the fibres, the matrix can positively or adversely affect the overall strength of the composite. The two properties that directly affect the stress transfer ability of a composite are the adhesion of the matrix to the fibre and the modulus of the matrix itself. The resin matrix that bonds the structure together acts as a load transfer mechanism between the fibres that are tightly bound to the structure [3-7]. Resin matrixes resist corrosion, protect the fibres from external damage, and increase the toughness and resistance against surface impacts, cuts, abrasion, and rough handlings. Resin systems are made up of multiple chemical families; its goal is to provide structural performance, cost, and precipitate positive environmental impacts [8].

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II. MECHANICAL PROPERTIES PREDICTION FOR ORTHOTROPIC MATERIALS

There are a number of approaches and formulas that predict different outcomes having been used for composite materials. The differences of these methods are due to the complexity and poor knowledge of the interaction between fibres and matrixes, and there are several factors that influence these methods, such as the laminate layup, experimental settings, and the effect of manufacturing techniques [2, 9]. The purpose of this section is to review the previously reported procedures and models that have been completed to obtain the mechanical properties of woven composite.

A number of micromechanical models have been suggested as possible candidates to evaluate the mechanical properties of composites materials. It can be divided into classes, namely phenomenological, empirical, elasticity approach, and homogenisation models. Nowadays, there are a number of software that is able to calculate these properties, such as the laminator, composite pro 3TEX version of Orientation Averaging analysis, and ESP [10, 11]. The important engineering constants in a fibre-reinforced lamina are elastic longitudinal and transversal moduli (E_1, E_2), Poisson's ratio (ν_{12}, ν_{21}), and the shear modulus (G_{12}). These elastic characteristics may be determined experimentally or by theoretical formulas. The simplest and most widely known formulation is called the rule of mixture. To utilise this method, the ISO strain elongation in the fibre, matrix, and composite are assumed to be equal.

$$\varepsilon_f = \varepsilon_m = \varepsilon_c \tag{1}$$

Where: $\varepsilon_f, \varepsilon_m, \varepsilon_c$ Strain in fibre, matrix and composite respectively.

Then, the longitudinal stress can be calculated:

$$\left.\begin{array}{l} \sigma_f = E_f \varepsilon_f \Rightarrow E_f \varepsilon_c \\ \\ \sigma_m = E_m \varepsilon_m \Rightarrow E_m \varepsilon_c \end{array}\right\} \tag{2}$$

The tensile force applied to the lamina is sheared by the fibre and the matrix, and as a result:

$$\sigma_c = \sigma_f \frac{A_f}{A_c} + \sigma_m \frac{A_m}{A_C} \tag{3}$$

Where:

σ_c: Tensile stress in the composite

A_f : Net c ross-sectional area for the fibres

A_m : Net cross-sectional area for the matrix

$A_c = A_f + A_m$

Since $V_f = \frac{A_f}{A_c}$ and $V_m = \left[1 - V_f\right] = \frac{A_m}{A_c}$, then:

$$\sigma_c = \sigma_f V_f + \sigma_m (1 - V_f) \tag{4}$$

Dividing both sides of Eq. (4) by ε_c, and by using Eqs. (2) and (3), the longitudinal modulus for the composite can be calculated from the equation below:

$$E_l = E_m + V_f (E_f - E_m) \tag{5}$$

And by using the same derivative procedure, the transverse tensile modulus for composite materials can be calculated from the equation below:

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$$E_t = \frac{E_f E_m}{E_f - V_f (E_f - E_m)} \tag{6}$$

And the shear modulus and Poisson's ratio can be calculated from the equation below:

$$v_{12} = v_f V_f + v_m V_m \tag{7}$$

$$v_{21} = \frac{E_{22}}{E_{11}} v_{12} \tag{8}$$

$$G_{12} = G_{21} = \frac{G_f G_m}{G_f V_m + G_m V_f} \tag{9}$$

III. EXPERIMENTS

A. Hand Layup Technique

Hand layup is a technique that is used in the manufacturing process of this research. This technique is a traditional composite processing method, which involves manually positioning the reinforcement mat or woven roving in the open mould, and resin is poured, brushed, or sprayed over onto the glass. This method has the advantage of minimising surface roughness and specifying cutting pressure [12, 13]. Generally, the process starts with the manual removal of entrapped air using squeegees or rollers. The most commonly used matrix resin in this process is room temperature curing epoxies. Belingardi [14, 15] reported that hand layup (HL) is the most widely used composite manufacturing technique. In order to produce high quality surfaces, a pigmented gel is first applied to the mould by spraying. After curing, the items used in the fabricating technique, such as the brush, wax and glass etc., are removed from the mould and used to apply a finish to the exterior. Liu [16] described the advantages of hand layup as being able to produce large and complex items with minimum equipment at low costs, which allows for more design flexibility. However, this method is not without its disadvantages, an example of which is longer curing time, as it requires a highly skilled operator and results in high amounts of materials being wasted. In addition, Avila [17] iterates that its stacking sequence, morphology, and the curing process directly influence the mechanical properties of composites produced by this method.

B. Materials and Equipment

The material selected for usage is carbon woven fibre, due to its superior characteristics compared with filament winding composites. Based on that fact, woven roving fibres were selected as the finest material for the hand lay-method. Moreover, the intertwining fibre structural design prevents fibre failures such as micro buckling and gross delamination [17-19]. The woven roving fibre is relatively cheap, possessing excellent strength, corrosion resistance, and high impact resistance. Furthermore, the selected matrices are epoxy resin (EP-A215C1) and hardener (EP-B215), generally used for hand layup that cures at room temperature. The low viscosity allows for easy handing and provides good wetting of reinforcements and substrates. They were mixed at the ratio of $100:20$ respectively by volume, as recommended by the manufacturer.

C. Specimens Fabrication Procedure

The woven roving fibre was positioned manually onto one plate of glass and the epoxy resin was brushed over and into the woven roving fibre. Safety was prioritized during this process. Masks and plastic gloves were worn at all times to prevent any inadvertent skin contact. In the preparation of the specimens, two glass plates were used, and a couple of layers of thin flexible plastic were applied to cover the glass plates in order to prevent the epoxy resin from directly touching the glass plates.

Fabrication began with fixing the fibre onto the glass plate, followed by preparing the mixture of the epoxy resin and the hardener, at a ratio of 100 unit volume of epoxy resin with 20 unit volume of hardener. The mixture of the epoxy and hardener has to be perfect and quick in order to avoid hardening before the fabrication could stop. After that, the mixture was brushed onto the fibre in equal distribution to produce balanced and symmetrical dimensions specimens. Subsequently, the second glass plate is added onto the specimen. After the fabrication procedure is completed, the brush, table, and all of the tools used in this stage were sanitised using thinner fluid. By then, the specimens were covered with fibre-epoxy composite. They were left for at least eight hours to ensure that the epoxy resin is completely dry. In this research, the specimens were exposed to air for ten hours in order to ensure that the curing of the epoxy was complete. Once the epoxy hardened, the specimens were removed for the finishing process. Moreover, the fibre volume of the specimens fell within the range of 50-56 per cent. The final stage of fabrication would be the cutting process. The size of the specimen was estimated by drawing the required lines on the surface of the specimens using a roller and a marker pen. Then, the specimens were cut based on these lines. The individual specimens were then carefully measured to ensure that they had similar dimensions.

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D. Mechanical Properties Test

The monotonic tension test is regarded as a basic mechanical testing prerequisite for materials. The test was carried out to determine the ultimate strength, stress-strain relation, and to develop a comprehensive knowledge of carbon/epoxy composite material used in this research. The author used the servo-hydraulic INSTRON machine for this purpose. The machine is connected to a computer to view and interact with the result; it is also supported by software used to calculate the mechanical properties, conduct post analysis, and documentations (See Fig. 1). The tensile test speed is set at a constant value of $1\,mm/\min$ up to the fracture stage according to conventional standards. Five specimens were fabricated based on ASTM (American Society for Testing and Materials) D3039, while the specimens' average detailed dimension is presented in Table 1. The tensile tests were carried out at a room temperature of $20^\circ C$ [17-18].

Fig. 1 INSTRON tensile test machine

TABLE 1 CARBON/EPOXY COMPOSITE

Specimen	**Width** (B) (mm)	**Length** (L) (mm)	**Gauge Thickness** (mm)	**Gauge length** (mm)	**Tensile strength** (MPa)	**Failure strain**	**Young Modula's** (MPa)
1	31.12	250	5.48	134	893.383	0.014	63813.078
2	31.36	250	5.87	134	882.227	0.013	67784.003
3	30.93	250	5.67	137	929.042	0.013	69301.805
4	31.42	250	5.37	138	910.413	0.013	68423.916
5	30.69	250	5.68	137	856.672	0.013	65897.897
Average	31.104	250	5.469	136	894.347	0.013	67044.140

The preparation of the test specimens was designed and manufactured based on the ASTM/D3039 standards. This standard is generally used for the determination of the tensile properties of the reinforced materials [17-18]. Each test specimen was made up of eight layers of fabric lamina to provide a symmetrical balanced angle-ply laminate, as recommended in the standard, and the stack sequence of the ply was $0/90^\circ$. Resins and hardener were used as the matrix of the composite material, as it is considered the most applicable material in this context [19]. The experimental work consists of the materials used, specimen preparation, finishing process, and testing. ASTM recommended that the specimens should have an end grip tab. A rectangular cross section grip is suggested for use with composites in order to feast the gripping force over the potential area, protect the outer fibres of the specimen, and accordingly minimise the damage to the specimens. Moreover, the grips used were specifically manufactured for composites. It is important to regulate the specimens and the grips accurately, as any

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misalignments will result in different stresses in the specimens. To ensure that the alignment is perfect, the gauges should have similar reading [17, 20]. The dimension of a typical tensile ASTM specimen is between the ranges of 10–30 mm wide, with a length of 200–250 mm, and a maximum thickness of 10 mm [18]. A calliper with an electronic digital display was used to measure the specimen's magnitudes to ensure the accuracy of the dimensions. After measurement and inspection, the specimen was mounted onto the machine grips. Then, the grips were carefully tightened to avoid axial stresses or damages.

IV. NUMERICAL ANALYSIS APPROACH

Composite relies on laminates, layup, fibre orientation, and the number of plies. The material used for the model is a symmetrical composite made from carbon fibres reinforced with epoxy. The thickness of the each ply is 0.60 mm, with a symmetric layup of 90°, which is identical to the experimental model. Several fibre plies were oriented in dissimilar directions from each laminate. Aligning the plies direction in the material properties is a form of customization to the composite that is intended to cater the composite to its potential applications. Moreover, the elements' orientation is an important parameter, as it is aligned to the geometry of the gear and is quantified in the global coordinate system. The stacked solid element is used for three-dimensional orthotropic materials. Above and beyond, the material properties and the dimensions of the laminate were based on the experimental tests results to ensure realistic outcomes in terms of material behaviour. After defining the mechanical properties of the material in the finite element (FE) model, a solid section for the coupons used in the simulation was assigned and created.

Similarly, the hypothesis is that the finite element models are an almost perfect representation of the actual composite materials. However, if the hypothesis is accurate, then the performance of the composite will have similar results with the experimental stage, but, if the hypothesis is improper, then it is essential to enhance and further simulate the models until the statistical results for the models and the physical composite ended up with an acceptable percentage of error (converge).

V. RESULTS AND DISCUSSION

A. Static Test Results

The individual sample tensile test results and dimensions for all the composites are presented in Table 1. The average details of the coupons' results are shown in Table 2. The effective young's modulus of the materials in the warp and fill directions have been calculated from the results obtained experimentally. From the stress-strain plots for the tensile test loading in the warp and fill directions, they seem to approximately demonstrate linear behaviour until the ultimate failure, which occurs suddenly. The stress levels in both directions almost have similar values. The average stress level for the carbon/epoxy is 894 MPa. It is observed from Fig. 2 that the results show a good match and similar behaviours. In addition, it can be experimentally realized that the stress-strain plots show minor nonlinear behaviour, due to the matrix cracking prior to fracture, as illustrated in Fig. 2. The effective shear modulus of the material has been determined using the phenomenological models based on the experimental results. The major Poisson's ratio is experimentally calculated by dividing the transverse strain by the axial strain, while the specimens were subjected to a uniform stress. This property value is ideally constant within the linear elastic section. Extensometers have been used to measure Poisson's ratio. In addition, the properties in the warp direction of the woven composite laminate are symmetric to the fill direction properties, and similar for shear and passion's ratio. Furthermore, the results exhibited appropriate elastic properties when compared with other approaches used by [21-24] for carbon/epoxy.

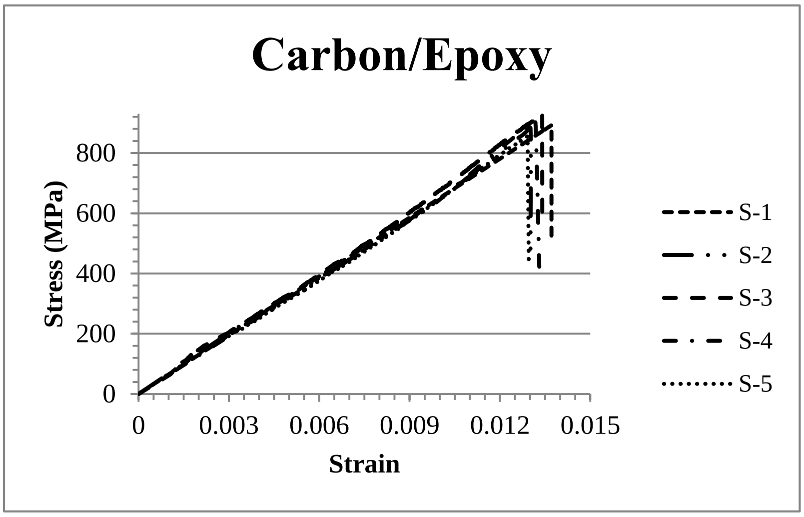

Fig. 2 Carbon/Epoxy Composite Stress-Strain Curve

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TABLE 2 TENSILE TEST AVERAGE RESULTS

Property	Carbon/Epoxy
Longitudinal tensile modulus (GPa)	67
Transverse tensile modulus(GPa)	5.60
Major Poisson's ratio	0.26
Minor Poisson's ratio	0.35
Shear modulus, G_{12} (GPa)	5.31
Shear modulus, G_{23} (GPa)	3.07

B. Numerical Results and Model Validation

It is essential to note that composite materials' modelling is complex, and there are several factors that might significantly affect the model. Therefore, validation is required to ensure that the model and the physical testing are accurate. The verification is based on the experimental source, using the ASTM D3039 standard. The finite element model outcomes have to be compared with the experimental results that were obtained previously. This comparison helps determine if the simulation results are reasonable, and that the properties analysed were precisely based on true principles of experimental results. After confirming the accuracy of the procedures used to model the composite, the same techniques were used in the bevel gear geometry. The numerical results for the rectangular specimen have been compared with the experimental carbon/epoxy specimen no.3. The specimen has an 8-ply symmetric composite made from carbon/epoxy, with 0.59 ≈ 0.60 mm ply thickness, which is identical to the experimental coupon. The specimen was meshed using solid elements possessing layer capability in ABAQUS. A non-linear static analysis has been performed using ABAQUS in the X - direction of the coupon. It is observed from Fig. 3 that the overall behaviour of the numerical stress and strain is very close to the experimental results. In addition, the failure criterion chosen for the composite materials is the maximum principle stress, as shown in Fig. 4.

It should be noted that the experimental results possess some minor nonlinearity, while the numerical outcomes indicate linear behaviour. The reason for that is the experimental testing result in the matrix cracking, which causes fluctuation; unlike the FEA outcomes, which assumed ideal circumstances. It was determined that the stress value of the FEA is 884.4 MPa, with a strain value of 0.012, which is slightly lower than the experimental results (coupon no.3 ultimate stress 929 MPa). Another vital observation from Fig. 5 is that the failure position prediction has a virtually similar location on the gauge length of the coupon. Consequently, without additional considerations on these curves, it is established that the numerical analysis outcomes and the experimentally tested composite demonstrate minor differences, and are within 5.059 percentage of error.

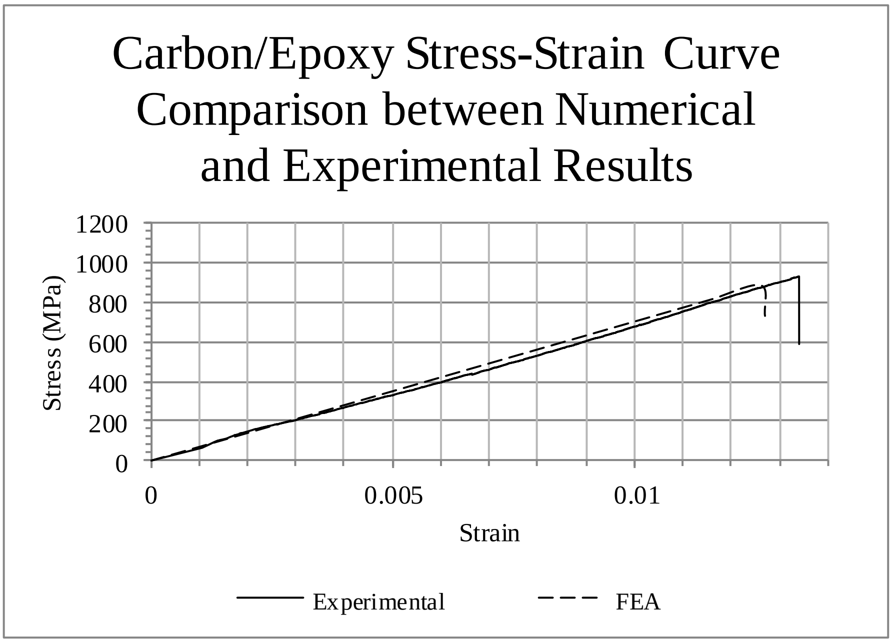

Fig. 3 Numerical and experimental tensile test results

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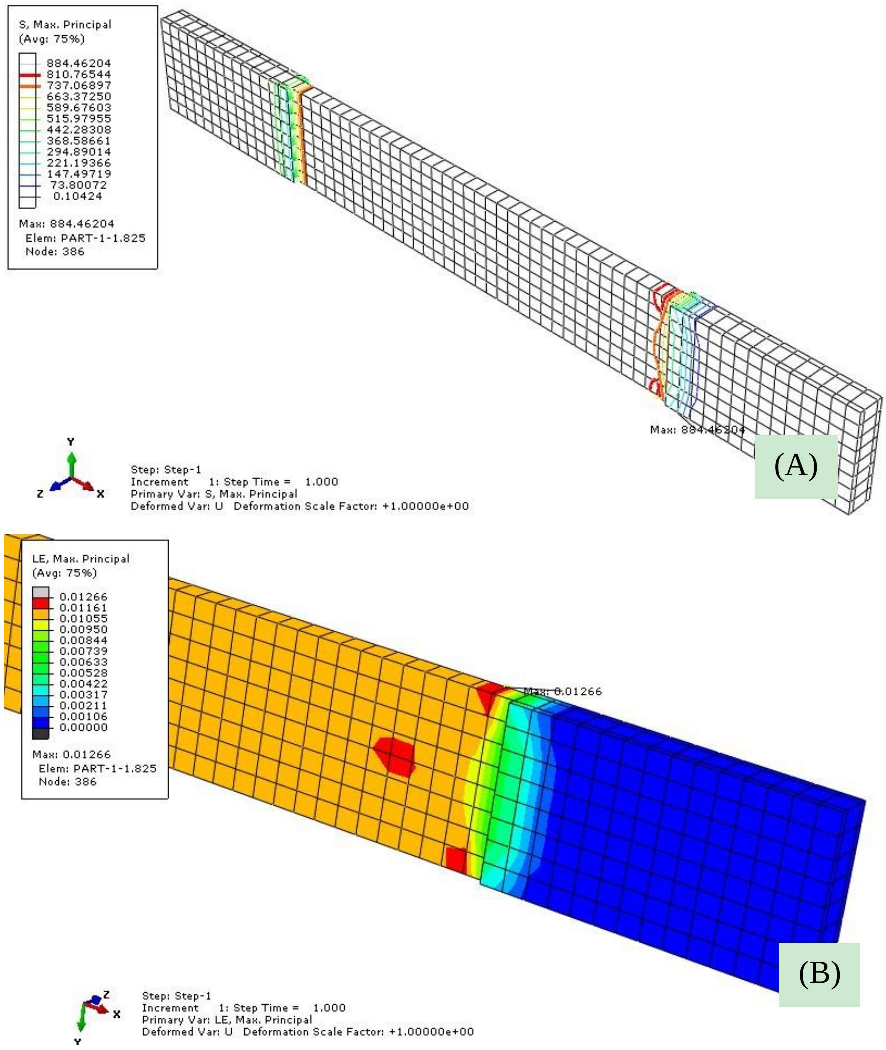

Fig. 4 Carbon/Epoxy composite materials coupon: (A) coupon maximum principle stress and (B) coupon strain

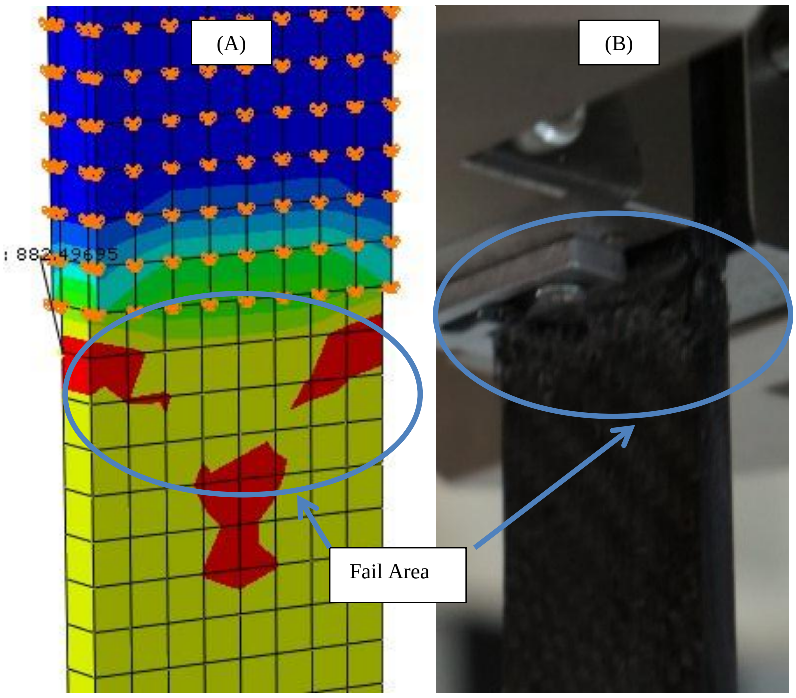

Fig. 5 Visualisation of critical areas that expected to fail in the (A) numerical analysis and (B) experimental coupons

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VI. CONCLUSION

The experimental tensile test was used to determine the mechanical performance of woven carbon/epoxy composite. The tested coupons showed a linear stress–strain curve behaviour. The reason of the slight non-linearity of the stress-strain curves is due to the matrix cracking during the test. The finite element models showed good agreement, and were accurate enough compared to the experimental data. From the numerical stage presented, it is possible to develop finite element method to produce accurate models, which is capable of simulating the woven carbon/epoxy composite's geometry.

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