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# **Fracture mechanisms and failure analysis of carbon fibre/toughened epoxy composites subjected to compressive loading**

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## **ABSTRACT**

This study investigates the failure mechanisms of unidirectional (UD) HTS40/977-2 toughened resin composites subjected to longitudinal compressive loading. A possible sequence of failure initiation and propagation was proposed based on SEM and optical microscopy observations of failed specimens. The micrographs revealed that the misaligned fibres failed in two points upon reaching maximum micro-bending deformation and two planes of fracture were created to form a kink band. Therefore fibre microbuckling and fibre kinking models were implemented to predict the compressive strength of UD HTS40/977-2 composite laminate. The analysis identified several parameters that were responsible for the microbuckling and kinking failure mechanisms. The effects of these parameters on the compressive strength of the UD HTS40/977-2 composite systems were discussed. The predicted compressive strength

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using a newly developed combined modes model showed a very good agreement to the measured value.

**Keywords:** Polymer-matrix composites (PMC); Analytical modelling; Carbon fibre reinforced polymer (CFRP) composites; Compressive strength; Failure analysis

## **1. Introduction**

Over the past three decades, much effort has been devoted to understand the failure mechanisms and develop models for predicting the strength of UD and multidirectional laminates loaded in compression. In polymer composites, the identification of critical failure modes is not easily accomplished because fracture of composites is usually instantaneous and catastrophic. Several types of possible failure modes, such as Euler buckling or macrobuckling of the specimen, crushing of the specimen end and longitudinal splitting, interfacial failure, elastic microbuckling of fibres, plastic microbuckling of fibres in a kinking mode and shear failure of the specimen, have been observed and reported in previous studies [1-18]. Among all failure modes, the fibre microbuckling failure mode is recognized as the dominant compressive failure mechanism in currently used continuous fibre/polymer matrix composite systems.

The earliest development of fibre microbuckling failure models presented that the continuous fibres are usually represented by initially straight long columns that support most of the applied loads [14]. The microbuckling of the fibres occurs when the system is loaded in compression and this leads to catastrophic failure at the maximum applied load. However, the obvious imperfection observed in manufactured continuous

FRP composites is fibre waviness or fibre misalignment, as shown in Fig. 1(a), therefore the fibres cannot be treated as straight and parallel layers [15]. The compressive failure is, most probably, caused by the local instability of fibres embedded in the matrix. The local instability of the FRP composites may be nucleated locally by fibre waviness, free edge region, resin rich region and poor fibre-matrix interfacial bonding [12]. This locally initiated failure propagates under incremental load through the laminate and thus creates a narrow zone called kink band width within the  $0^\circ$  plies, which lose structural integrity and collapse as shown in Fig. 1(c). Fibre waviness or fibre misalignment has been reported to have a detrimental effect in CFRP systems by numerous researchers [5-12]. Since the fibre waviness can not be avoided during the manufacturing processes, this imperfection should be taken into consideration in the prediction of overall strength of the CFRP systems when loaded in compression.

In this study, the failure mechanisms of UD HTS40/977-2 toughened resin composites subjected to longitudinal compressive loading were investigated. The compression and in-plane shear tests were conducted based on CRAG test method [19] and ASTM standards. A possible sequence of failure initiation and propagation was proposed based on SEM and optical microscopy observations of failed compression specimens. Fibre microbuckling and fibre kinking failure models were implemented to predict the compressive strength of UD HTS40/977-2 composite laminate such as Budiansky's model [18], Berbinau's model [12] and a newly developed combined modes model. The effects of several parameters, such as shear stress-strain properties, initial fibre misalignment, initial half wavelength, fibre diameter and its properties, fibre volume fraction and manufacturing methods on the compressive strength of the UD HTS40/977-2 composite systems were also discussed.

## **2. Experimental Details**

### *2.1 Materials and test procedures*

The specimens were fabricated from carbon fibre/epoxy pre-impregnated tapes of 0.27 mm thickness and 300 mm tow width. The prepreg tapes were made of UD continuous high tensile strength carbon fibres (Toho Tenax HTS40 12K 800tex) pre-impregnated with Cycom<sup>®</sup>977-2 toughened epoxy resin. This is the same toughened resin used in modern aircraft construction such as Boeing 787 and Airbus A380. The HTS40/977-2 prepreg tapes are commercially available and supplied by Cytec Engineered Materials Ltd. The pre-impregnated HTS40/977-2 tapes were hand lay-up to manufacture an eight-ply UD panel and a  $[\pm 45^\circ]_{2s}$  laminate. The laminates were cured in the hot press at 177°C for 3 hours in accordance to standard curing cycle recommended by manufacturer.

The compression test was conducted in accordance to CRAG test method [19] and ASTM Standards D3410 and D6641. A short gauge-length  $[0]_8$  specimen of 10 mm to 13 mm was used to evaluate UD material compressive properties. 120 $\Omega$  strain gauges were used to monitor the degree of Euler bending, measure the axial strain, and to determine the compressive modulus and the Poisson's ratio of the UD laminate. A 250 kN servo-hydraulic machine with the Imperial College of Science Technology and Medicine (ICSTM) test fixture design [16] was used to determine the compressive behaviour of the UD laminate at a constant compression rate of 1 mm/min. Several tests were stopped before the final failure occurred in order to examine the initial failure mode. The fractured specimen was prepared using the standard metallographic technique to be observed under the optical microscope at 50x to 1000x magnification.

The post-failure surfaces of the compression specimens were also observed under Scanning Electron Microscopy (SEM) to identify the failure mechanisms involved during compression.

The in-plane shear test was a uniaxial test of a  $\pm 45^\circ$  laminate and performed in accordance with the CRAG test method [19] and ASTM Standards D3518 and D3039. The tensile load was increased uniformly, at 5 mm/min testing speed rate, to cause failure within 30-60 seconds. A specimen of 100 mm gauge length was used to evaluate in-plane shear properties. The in-plane shear stress in the material coordinate system was directly calculated from the applied axial load whilst the related shear strain was determined from the longitudinal and the transverse normal strain data collected by the strain gauges.

Full details on the characterization methods and experimental techniques had been documented previously by Jumahat et al [20]. The compressive stress-strain and in-plane shear stress-strain responses and failure characteristics were described in sections 2.2 and 2.3 for modelling purposes. The overall properties of the material used in this study were summarized in Table 1. These parameters will be used to predict the compressive strengths of UD HTS40/977-2 composite laminate using several types of failure models as summarized in Table 2.

## *2.2 Compressive properties and failure modes*

Previous work by Jumahat et al [20] has shown that the compressive stress-strain response of the UD HTS40/977-2 composite laminate was linear up to a strain of 0.6%, as shown in Fig. 2(a), with the elastic modulus of 112 GPa. Fig. 2(a) shows that at higher strains the response becomes non-linear and the tangential modulus at failure is

42% lesser than that of the initial linear part. This material softening is due to the damage in the form of fibre microbuckling (fibre instability failure mode) and plastic deformation of the resin. Catastrophic failure occurred at the average failure stress of 1396MPa and the strain at failure of -1.5%. The acceptable failure modes and areas of the UD composite laminate after compression are described by ASTM Standards D3410 and D6641. The overall specimen failure schematics are shown in Fig. 2(c). The fractured specimen of UD HTS40/977-2 after being loaded in compression is illustrated in Fig. 3(a). This is an acceptable failure mode according to ASTM Standards D3410 and D6641, which is identified as transverse shear near top grip/tab failure mode (code TAT). The initial failure mode was examined using an optical microscope at 200x magnification as shown in Fig. 4. Fig. 4 reveals that the failure was initiated by fibre microbuckling. The fibres break at two points, and create a kink band inclined at an angle of approximately  $\beta = 18^\circ$  to the transverse direction (see Fig. 4). The fibres within the band were rotated by the angle of  $\phi = 35^\circ$  from the initial fibre direction, and the kink width  $w = 60\text{-}100 \mu\text{m}$  was approximately equal to 8-15 fibre diameters ( $d_f = 7 \mu\text{m}$ ). Post-failure examination of the fractured surfaces using a scanning electron microscope revealed also the fibre microbuckling failure mechanism as shown in Fig. 3. Fig. 3(c) shows the tensile and compressive surfaces on an individual fibre which failed due to fibre microbuckling.

### *2.3 In-plane shear properties*

Fig. 5(a) shows the in-plane shear stress-strain response of  $[\pm 45]_{2s}$  HTS40/977-2 composite laminate. The shear yield strength and initial fibre misalignment of the composite were measured using a similar method applied in Lee [16]. The shear yield

strength was 52 MPa at shear yield strain of 1.8% and the average initial fibre misalignment was  $0.92^\circ$ . The elastic shear modulus at 0.25% shear strain was 4.4 GPa and the plastic shear modulus measured using tangent at yield point was measured 680 MPa. The in-plane shear strength and the corresponding shear strain were 101.12 MPa and 17%, respectively. The analytical equation as described in Fig. 5 was used in the modelling work.

### **3. Compressive strength prediction models for UD HTS40/977-2CFRP composites**

In this study, the fibre microbuckling model developed by Berbinau et al. [12] and kink band model developed by Budiansky [18] were used to predict the compressive strengths of the UD HTS40/977-2 toughened composite systems. The experimentally observed fracture mechanisms involved both fibre microbuckling and subsequent plastic kinking. Therefore a combined modes model, which incorporated elastoplastic behaviour of shear stress-strain response, in the fibre microbuckling model was developed in conjunction with the plastic kinking model. This combined modes model was then used to predict the strength of UD HTS40/977-2 composite laminate. The physical and mechanical properties data obtained from the experimental work were incorporated into various models as summarized in Table 2.

#### *3.1 Fibre kinking model*

The theory for failure of composites in a kink mode, as illustrated in Figures 1 and 6, was proposed by Budiansky [18]. Fibre kinking is a result of the combination of compression and shear loadings. Budiansky's model assumes elastic-perfectly plastic matrix behaviour. The model suggests that when the elastic shear stress limit (the shear



yield point) is reached, the plastic deformation takes place causing failure. The compressive strength of UD laminate using kinking model, which was derived in [4,18], can be determined using the following equation:

$$\sigma_c = \frac{\tau_y \sqrt{1 + \left( \frac{\sigma_{Ty}}{\tau_y} \right)^2 \tan^2 \beta}}{\phi_o + \gamma_y} \quad (1)$$

where  $\tau_y$  is the in-plane shear yield strength,  $\sigma_{Ty}$  is the transverse yield strength,  $\gamma_y$  is the shear yield strain,  $\phi_o$  is the initial fibre misalignment angle and  $\beta$  is the kink band inclination angle of the composite. For a very small  $\beta$ , equation (1) yields at a minimum value of shear yield stress and the general expression for the compressive buckling stress is given by equation (2).

$$\sigma_c = \frac{\tau_y}{\phi_o + \gamma_y} \quad (2)$$

Fig. 7 shows the theoretical compressive stress  $\sigma_c$  versus fibre rotation response  $\Phi$  graph for HTS40/977-2 CFRP composite system. This graph was developed based on equation (2). The curve, as shown in Fig.7, describes the post buckling behaviour of the UD composite material which consists of (a) initiation of HTS40 fibres microbuckle, (b) the fibres breakage, (c) the matrix or interface between the matrix and the fibres fails and finally (d) the overall composite collapses. The predicted compressive strength of the UD laminate using Budiansky's model is about 1529 MPa (point B, Fig. 7). The system is assumed to fail when the elastic shear yield point is reached and plastic deformation has taken place causing catastrophic failure at point B. Equation (1) predicts the longitudinal compressive strength is 1588 MPa which is higher than the measured compressive strength.

### 3.2 Fibre microbuckling model

A unique fibre microbuckling model based on an initial sinusoidal shape of fibre has been developed by Berbinau et al [12], which accounts for all the factors that affect the compressive failure strength in UD fibre-reinforced composites such as non-linear shear stress-strain response, fibre type, fibre dimension and property, fibre volume fraction and configuration of fibre waviness (wavelength and misalignment angle). Berbinau's model assumes that the fibre acts as an Euler slender column supported by a non-linear matrix. Based on the fact that carbon fibres in the  $0^\circ$  UD laminates are not perfectly aligned with the loading direction, up to  $5^\circ$  fibre misalignment, Berbinau et al [12] modelled the initial fibre waviness by a sin function  $v_0(x)$  as shown in Fig. 8(a). A sine function  $v_0(x)$  is characterised by its amplitude  $V_0$  and its half-wavelength  $\lambda_0$  as follows:

$$v_0(x) = V_0 \sin\left(\frac{\pi x}{\lambda_0}\right) \quad (3)$$

Fig. 8 shows when the compressive load is applied the misaligned fibre deform into a new sine function  $v(x)$  of amplitude  $V$  and half-wavelength  $\lambda$ . The function  $v(x)$  is given by:

$$v(x) = V \sin\left(\frac{\pi x}{\lambda}\right) \quad (4)$$

Based on the assumption of fibre buckling in-phase (fibres kink in-phase with one another), all fibres deform the same way therefore  $p = q = 0$ . Additionally, a constant axial force  $P$  is used to reduce the equilibrium conditions for the transverse forces and bending moments into the following equilibrium equation:

$$\frac{d^2 M}{dx^2} + P \frac{d^2 v}{dx^2} + \frac{dm}{dx} = 0 \quad (5)$$

Noting that,

$$\frac{d^2 (v - v_0)}{dx^2} = \frac{M}{E_f I_f}, \quad (6)$$

$$\frac{dm}{dx} = -A_f G_{12}^{ep}(\gamma) \frac{d^2 (v - v_0)}{dx^2}, \quad (7)$$

$$\sigma_{\text{fibre microbuckling}} = \sigma_0 = \frac{PV_f}{A_f}, \text{ and} \quad (8)$$

$$G_{12}^{ep}(\gamma) = G_{12}^e \exp\left(-\frac{G_{12}^e \gamma}{\tau_y}\right) + G_{12}^p \exp\left(-\frac{G_{12}^p \gamma}{\tau_{ult} - \tau_y}\right) \quad (9)$$

Substitute equations (6) to (9) into equation (5) hence the equation becomes:

$$E_f I_f \frac{d^4 (v - v_0)}{dx^4} + \frac{A_f \sigma_0}{V_f} \frac{d^2 v}{dx^2} - A_f G_{12}^{ep}(\gamma) \frac{d^2 (v - v_0)}{dx^2} = 0 \quad (10)$$

where  $E_f$  and  $I_f$  are the elastic modulus and the second moment of area of the fibre respectively,  $A_f$  is the fibre diameter,  $V_f$  is the fibre volume fraction,  $G_{12}^{ep}(\gamma)$  is the experimental nonlinear shear modulus in a function of the shear strain,  $G_{12}^e$  and  $G_{12}^p$  are the elastic and plastic in-plane shear modulus, respectively and  $\tau_y$  and  $\tau_{ult}$  are the yield and ultimate shear stress, respectively. The analytical shear stress-strain equation for toughened resin composite systems, as shown in Fig. 5(a), is given by:

$$\tau(\gamma) = \tau_y \left(1 - \exp\left(-\frac{G_{12}^e \gamma}{\tau_y}\right)\right) + (\tau_{ult} - \tau_y) \left(1 - \exp\left(-\frac{G_{12}^p \gamma}{\tau_{ult} - \tau_y}\right)\right) \quad (11)$$

In this study, Equation (10) was solved numerically using the Fortran programming language. This programme was compiled and executed via commercial Fortran compiler to predict the compressive strength of UD HTS40/977-2 CFRP composite. The result was given by a relationship between the applied compressive

stress  $\sigma^\infty$  and the maximum amplitude  $V$  of the buckled fibre during uniaxial compression. Failure of the UD material occurred when the fibre amplitude  $V$  started to increase asymptotically. Fig. 9 (a) presents the maximum amplitude  $V$  of the  $0^\circ$  buckled fibre versus the applied stress  $\sigma^\infty$  for UD HTS40/977-2 composite laminate. The curve shows that  $V$  increases slowly with increasing applied stress  $\sigma^\infty$  and then grows exponentially until it reaches the maximum strength  $\sigma_0$ , where the curve increases asymptotically. The predicted longitudinal compressive strength was 1059 MPa, which was 24% lower than the experimentally measured compressive strength.

### *3.3 Combined modes model (fibre microbuckling and plastic kinking)*

The combined modes model was developed based on Berbinau et al. [12] fibre microbuckling model and Budiansky [18] fibre kinking model. Berbinau's model underestimates the actual compressive strength value because the predicted compressive strength is the critical stress at which the fibres fail via microbuckling rather than the final failure stress of the whole laminate caused by both fibre microbuckling and plastic kinking mechanisms.

In the fibre microbuckling analysis (section 3.2), the compressive strength of the composite depends only on the strength properties of the misaligned fibre, which is supported by the non linear matrix, without taking into account the additional compressive strength of the laminate after the fibres break, which is governed by plastic deformation of the composites. The plastic deformation of the composite after the fibre breaks should be included into the compressive strength model to predict the actual compressive strength based on the actual phenomena observed through the experiment.

The plastic kinking failure mechanism is incorporated into the model as the following equation:

$$\sigma_c = \sigma_{\text{fibre microbuckling}} + \sigma_{\text{plastic kinking}} \quad (12)$$

where the additional compressive strength caused by plastic deformation,  $\sigma_{\text{plastic kinking}}$  of the composite can be determine using modified Budiansky's model as the following:

$$\sigma_{\text{plastic kinking}} = \frac{\tau_{\text{ult}} - \tau_y}{(\gamma_{\text{ult}} - \gamma_y) + \phi_o} \quad (13)$$

The actual predicted compressive strength using combined modes model, equation (12), was 1334 MPa which gave an accurate value of predicted compressive strength as shown in Fig. 9(b). Therefore the combined modes model was the most suitable model to predict the compressive strength of UD toughened resin composite laminates.

#### **4. Factors influenced the compressive strength of UD HTS40/977-2 CFRP composites**

The fibre waviness of 0° fibre induced significant matrix shear stresses and strains for a given axial compressive stress level. Experimental observation in [21] showed that as the shear modulus and the shear yield strength of the laminate increased, the compressive strength also increased. In this study, the effects of various parameters on the compressive strength of UDHTS40/977-2 CFRP composite were examined using combined modes model (Eqn. 12). The shear yield stresses of 45 MPa to 68 MPa and initial fibre misalignments of 1° to 5° were used in the analysis since these were normally observed values in CFRP composites. 8 to 15 fibre diameters of initial half wavelength were used as input parameter in the analysis since these values were

observed experimentally. The normally observed fibre volume fractions for CFRP composites of 0.55 to 0.65 were used in the analysis. The parametric study was conducted based on programme outline in Table 3. Additionally, the effects of fibre types and properties, such as HTS40, T800 and IM7, on the compressive strength of the HTS40/977-2 UD composite laminate were also studied.

#### *4.1 The effects of non-linear shear stress-strain response*

The shear stress-strain behaviour of UD HTS40/977-2 composites, which have maximum shear strength of 85 MPa, 115 MPa and 130 MPa, was predicted using equation (11). The input data were summarized in Table 3. The effects of shear properties on the compressive strength of the UD HTS40/977-2 composite laminates are illustrated in Fig. 10. Fig. 10(a) shows that the predicted fibre microbuckling compressive stress increases with the increasing shear strength. The fibre microbuckling compressive stresses increase of about 11%, 24% and 36% at shear strengths of 101 MPa, 115 MPa, and 130 MPa, respectively. The total compressive strength is predicted using combined modes model, as shown in Fig. 10 (b). This analysis showed that shear properties had a great influence on the overall compressive strength of the CFRP composites. A system which has higher shear properties improves the compressive strength, due to the stiffer matrix which provides a better support to the fibre against failure and thus more stress is needed to deform the composite structures.

#### *4.2 The effects of initial fibre misalignment angle*

The non-linear shear stress strain diagram was used to determine the shear yield stress and strain at several initial fibre misalignment angles as illustrated in Figure 11.

The input data, which were determined from Figure 11, were summarized in Table 2. The effects of initial fibre misalignment on the compressive strength of the UD HTS40/977-2 composite laminates are illustrated in Figure 12. Figure 12(a) shows that the microbuckling stress drops from a value of 919 MPa at 1° initial fibre misalignment to a value of 648 MPa at 2° initial fibre misalignment and decreases to 330 MPa at 5° initial fibre misalignment. A huge reduction in compression strength of about 30%, 46% and 64% at 2°, 3° and 5° initial fibre misalignment, respectively, indicate that this parameter gives the most significant effect to the strength of the UD composite laminate compared to shear stress-strain properties. A better CFRP system can be achieved if the initial misalignment of the fibre can be minimized.

Figure 12(b) shows the total compressive strength which consists of fibre microbuckling and plastic kinking failure stresses. A smaller initial fibre misalignment angle leads to a higher compressive strength. Theoretically, the smaller initial fibre misalignment gives the better stability of the fibre against the microbuckling stress. The compressive failure strength of HTS40/977-2 systems which has initial fibre misalignment of 5° is 61% lower than that of 1° initial fibre misalignment. A small variation of fibre waviness in the CFRP composites provides better fibre stability against microbuckling hence supports more load. Therefore a system which has small fibre waviness results in the better compressive properties because the stability of the whole structure is highly dependent on the effectiveness of the carbon fibres supporting the load. The fibre waviness is very difficult to control during the manufacturing processes. Investigation on development of toughened resin is very important to improve the properties of the matrix supporting the fibres such as minimizing coefficient thermal expansion mismatch between the matrix and the fibres during curing

which can lead to a low fibre misalignment. A low fibre waviness and high shear properties are desirable in the advanced CFRP composite systems.

#### *4.3 The effects of initial half wavelength*

In this study, the initial fibre half wavelength was measured from a microscopic observation of the 0°-ply, as illustrated in Fig. 4. For the UD HTS40/977-2 system the fibre half-wavelength was equal to the kink band width of 60  $\mu\text{m}$  to 100  $\mu\text{m}$ . Hence, the fibre half-wavelength was of the order of 8 to 15 fibre diameters. The effects of fibre initial half-wavelength on the compressive strength of the UD HTS40/977-2 composite laminates are illustrated in Figures 13(a) and 14. Figure 13(a) shows that the fibre microbuckling stress drops from a value of 1071 MPa at  $\lambda_0 = 56 \mu\text{m}$  ( $\approx 8d_f$ ) to a value of 919 MPa at  $\lambda_0 = 70 \mu\text{m}$  ( $\approx 10d_f$ ) and decreases to 797 MPa at  $\lambda_0 = 105 \mu\text{m}$  ( $\approx 15d_f$ ). The microbuckling stress reduces for about 14%, 21% and 26% at 70  $\mu\text{m}$ , 84  $\mu\text{m}$  and 105  $\mu\text{m}$  fibre initial half-wavelengths, respectively. It shows that this parameter gives significant effect to the strength of the UD composite laminate. The shorter length of the initial half-wavelength gives a better resistance to fibre microbuckle deformation hence increase the compressive stress needed to break the fibre. Figure 14 shows that the compressive failure strength at  $\lambda_0 = 105 \mu\text{m}$  ( $\approx 15d_f$ ) is about 10% lower than that of  $\lambda_0 = 70 \mu\text{m}$  ( $\approx 10d_f$ ) and about 20% lower than that of  $\lambda_0 = 56 \mu\text{m}$  ( $\approx 8d_f$ ). This shows that a shorter fibre initial half-wavelength provides better fibre stability against microbuckling hence supports more load.

#### *4.4 The effects of fibre volume fraction and manufacturing methods*



Fibre volume fraction is one of the most important parameters in compressive strength predictions. In this analysis, a range of fibre volume fractions from 55% to 65% was used, as these are normally observed values for CFRP composites. Fibre volume fraction is dependent on the production or manufacturing processing methods used to fabricate the CFRP composite laminate. In this study, the fibre volume fractions of the UD HTS40/977-2 system cured using hot press and autoclave were 58% and 62%, respectively. These values were measured using image analyzer technique.

The effects of fibre volume fraction on the compressive strength of the UD HTS40/977-2 composite laminates are illustrated in Figures 13(b) and 14. Figure 13(b) shows the fibre microbuckling stress increases from a value of 835 MPa at  $V_f = 50\%$  to a value of 1086 MPa at  $V_f = 65\%$ . The microbuckling stress increases from about 10%, 20% and 30% at 0.55, 0.6 and 0.65 fibre volume fractions, respectively. It shows that this parameter gives significant effect to the strength of the UD composite laminate. The higher amount of fibre volume fractions the stronger the CFRP composites. This is because most of the load which is applied to the CFRP composites is supported by the fibre. After the fibre fails, the load is supported by the strength of the matrix. Figure 14 shows that the compressive failure strength at  $V_f = 55\%$  is about 8% higher than that of  $V_f = 50\%$  and about 14% lower than that of  $V_f = 65\%$ . This shows that a higher fibre volume fraction provides better fibre stability against microbuckling hence supports more load.

In order to study the effects of manufacturing processes on the compressive strength, the prepreg was cured in two different ways, hot press and autoclave methods. Using the same prepreg materials, the hot press method yielded  $V_f = 58\%$  while the autoclave produced a composite with  $V_f = 62\%$ . The overall compressive strength of

CFRP composite manufactured using autoclave method was 1308 MPa which is 10% higher than CFRP composite prepared using hot press method as shown in Figure 14. This improvement in compressive strength is mainly due to the increase in fibre volume fraction, additionally factors such as consolidation of the fibres and reduced void content, will also contribute to this observed improvement in compressive strength. A high quality CFRP composite manufactured using an autoclave can have as high as 65% fibre volume fraction. Therefore the selection of manufacturing methods is very important to determine the overall performance of the CFRP composite system.

#### *4.5 The effects of fibre types and properties*

Three types of graphite fibres, IM7, T800 and HTS40, were used to study the effects of fibre type and properties on the compressive strength of UD CFRP composites. The properties of Hercules IM7 and Toray T800 were available elsewhere, eg. [22] and the manufacturer datasheets. The fibre microbuckling stress of the CFRP system that used T800 carbon fibre has the highest critical stress of 977 MPa compared to CFRP made of HTS40 and IM7 carbon fibres as shown in Fig. 15(a). The overall compressive strength of T800/977-2 CFRP composite is 1250 MPa which is 3% and 1.5% higher than HTS40/977-2 and IM7/977-2 CFRP composite, respectively. HTS40 has bigger fibre cross-section area compared to IM7 and T800, however the compressive strength of HTS40/977-2 is lower than that of IM7/977-2 and T800/977-2 systems. This is because IM7 and T800 types of carbon fibres have higher modulus of elasticity compared to HTS40 carbon fibre.

## **5. Conclusions**

In this study, fibre kinking and fibre microbuckling models have been implemented to predict the compressive strength of the UD HTS40/977-2 toughened composite laminate. SEM micrograph revealed that the failure of the UD HTS40/977-2 composite laminate was initiated by fibre microbuckling and subsequent plastic kinking of the materials. Therefore a combined modes model was developed to predict the compressive strength of the system. The combined modes model yielded a successful compressive strength prediction in which the predicted compressive strength was in a good agreement to the measured value. Considering all the parameters that had been investigated, the in-plane shear properties and the initial fibre misalignment angle between the fibres and the loading axis were identified as the most critical parameters that affect the compressive strength of the UD toughened composite laminates.

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