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Research paper

Elastic Properties of Woven Fabric CFRP Composites

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Abstract

Synthetic fibers such as carbon fibers are widely used as reinforcing materials, to combined with matrix system to produce a high-performance composite material in industrial sectors. Elastic properties of composites are highly dependent upon various factors such as fiber types, fiber orientation, and composite coupon thickness. The elastic properties of twill weave carbon fiber reinforced polymer (CFRP) composite plate was investigated in experimental frameworks. This paper is to determine the mechanical properties and failure mode of CFRP composite plates. The effects of lay-up orientations and coupon thickness were concerned in current study as specified in testing series. Generally, all CFRP coupons failed and breaks within its gauge length. Cross-ply and thicker coupons demonstrates greater strength than quasi-isotropic lay-up counterparts due to larger 0˚ plies volume fiber fraction.

Keywords: *Woven fabric; CFRP; Composite plate; Elastic properties; Failure modes.*

1. Introduction

Compared to traditional engineering materials such as steel and concrete, composite materials offer excellent specific stiffness (and strength). This has led to these materials being used increasingly in most structures applications. More recently, the fabrication and processing cost of composite materials has fallen and composites are used much more widely in civil engineering structure applications especially in bridge rehabilitation and bridge structures components such as bridge deck and bridge girders.

Synthetic fibers were widely used as the reinforcement of composite material. The vast majority synthetic fibers that used in most of engineering sector were glass fiber and carbon fiber. Carbon fiber plies was found as thinner and larger specific strength compared to the glass fiber plies as reported from previous study [1]. Formerly, carbon fiber reinforced polymer (CFRP) is widely used in aerospace applications due to its excellent properties. Reduction of crimp by weaving pattern, twill or satin weave offers good drapeability but slightly unstable configurations compared to plain weave architectures.

Generally, polymer used in composite as matrix binder can be classified into two major classes, i.e., thermoset and thermoplastic polymers. Thermoplastic polymer commonly used in composite productions are polystyrene (PS), polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PV). On the other hand, epoxy resin, vinyl esters, polyester, and phenolic are category as thermoset polymer [2]. Strain at failure is varied depending on type of polymer matrix used in any composite, thermoset polymer (e.g., epoxy resin) provides relatively small elongation at break (ranging between 3% to 6%) com-pared to ductile thermoplastic polymers (more than 30%). Comparison of frequently used thermosetting polymers was reported by Bhutta et al. [3] that matrix type was less significant effect on composite strength where kenaf/epoxy composites showed the highest tensile strength (i.e., 78.92 MPa) than kenaf/polyester and kenaf/vinyl ester composites (i.e., 76.67 MPa and 78.34 MPa, respectively).

Woven fabric layer is a 2-D reinforcement obtained by interlacing two yarns orthogonally through weaving process and subsequently forming a crimping region. Bear in mind that fiber yarn weaved along longitudinal direction (i.e., applied loading direction) is referred as warp yarn (0º), while interlacing yarn perpendicularly to the loading direction referred as weft yarn (90º). Density of woven fabric fiber is determined by counting the number of yarns in warp and weft direction per centimeter. The woven fabric's reliability is sustained by the mechanical interlocking of the fibers. The capability of a fabric to fit in to a complex surface called drape. Drape, surface smoothness and the stability of a fabric are mainly con-trolled by the weaving pattern.

Common weaving architectures are plain weave, twill weave, and harness satin weave. A basic unit by interlacing each warp fiber passes alternately under and over each weft fiber is known as plain weave. The fabric is symmetrical, has good stability and reasonable porosity but has poor drapability and high-volume fiber crimping imparts relatively low mechanical properties compared with other weave architectures. Thicker fiber plain weave layer gives excessive crimping volume and not preferably used in thick fabrics. On the other hand, twill weave architectures are obtained when a warp fiber alternately crossing over and under two weft fibers in a repeated pattern to produce a visual effect of a straight or broken diagonal 'rib' to the fabric. Twill weave has superior wet-out and drapability over the plain weave with small reduction in stability. As crimping volume is reduced, the fabric has smoother surface and slightly higher mechanical properties. Final mechanical properties of composite materials are dependent upon weaving patterns of fiber yarn, although crimping region is associated with strength reduction, but the damage morphologies occurred may show otherwise.

Stacking sequence studies is available in unidirectional and woven fabric lay-up form in the literatures and it is important as fiber orientations contribute to tensile strength and modulus in a composite plate. Tholibon et al. [4] studied the mechanical properties of single layer (or ply) unidirectional kenaf polypropylene composite with different fiber orientation and found that 0˚ fiber direction exhibited excellent tensile strength and modulus compared to +45˚ and 90˚ fiber direction. This is due to inability of kenaf fiber to transfer the stress through fiber reinforcement along the longitudinal direction in +45˚ and 90˚ ply. Although less good tensile strength exhibited in +45˚ ply, but this ply provides good resistance against shear as maximum principal shear plane occurred at 45˚.
There are two major woven fabric lay-up types available, i.e., cross-ply and quasi-isotropic lay-ups. Cross-ply layer consists of primarily (0˚/90˚) plies with various plate thickness, e.g., (0˚/90˚)$_s$, (0˚/90˚)2s. On the other hand, quasi-isotropic consists of (0˚/90˚)s and (+45˚/-45˚) layers, commonly used stacking sequence are (0˚/90˚/±45˚)$_s$. Other fiber orientation is also regarded as quasi-isotropic lay-up, e.g. (±45˚)$_s$ and (0˚/±60˚)$_s$. The stacking sequence is preferably taken as symmetric and balanced laminates, a laminate which is neither balanced nor symmetric will in general shear, bend and twist under tensile loading: there is not only extension/shear coupling as occurs in an off-axis lamina, but also coupling between extension and bending and twist. Salman et al. [5] reported on woven fabric kenaf fiber composites with (0˚/90˚) and (45˚/-45˚) layers. They found that (0˚/90˚) layer showed the highest tensile strength and modulus in various thermoset polymers compared to (+45˚/-45˚) layer. This is due to better stress distribution in kenaf fiber along longitudinal and transverse directions in 0˚/90˚ layer. Besides fiber directions, stacking sequence of woven fabric fiber also affected on mechanical proper-ties of composite plate. Hamdan et al. [6] had investigated the effect of tensile and flexural properties on four stacking sequence of woven fabric kenaf composites and they found that highest strength presented on coupon with higher yarn density in longitudinal directions to support and resist the applied load. The aim of the present work is to determine the independent elastic and material properties and associated failure mode of twill weave CFRP composite with variation of lay-up types and coupon thickness under quasi-static loading.

2. Experimental methodology

2.1. Testing coupons preparation

The CFRP composite panels were fabricated by combining twill weave carbon fiber and resin system by the wet lay-up techniques under compression molding. Resin system was prepared by mixing epoxy resin SP84 and hardener SP76 with ratio 2:1, respectively. One layer of twill weave carbon fiber was placed on an adjustable aluminum mold smeared uniformly with resin system. The steps were repeated accordingly to desired stacking sequence as specified in testing series. After lay-up fabrication process, the wet lay-ups were allowed to set at least twenty-four hours curing period by using hydraulic compression machine under room temperature prior to demolding.
The fabricated panels were then cut according to testing coupon size by using cooling diamond saw. In separate study, all unnotched coupons were prepared with constant in-plane coupon sizes (i.e., coupon width and length), however, the variation only in coupon thickness according to number of stacked woven fabric layers and type of reinforcing fiber types. These coupons were used to determine independent material properties (i.e., unnotched strength) and elastic properties (i.e., Young's modulus, Poisson's ratio, and shear modulus) of each lay-up designation investigated. Coupon with length of 230 mm and 25 mm width were prepared prior to mechanical testing. The plate geometry of a testing coupon was given in Figure 1.

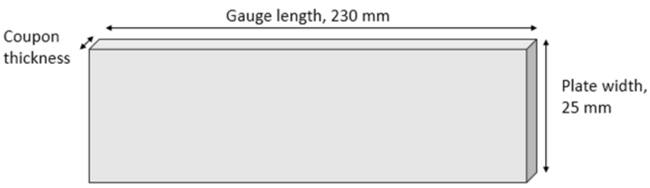


Fig. 1: Unnotched plate geometry

2.2. Testing series

An experiment framework was investigated to study the bearing stress at failure of twill weave CFRP hybrid joints with four different laminate lay-ups. There are two types of lay-up types understudied, i.e., cross-ply lay-up (CX2, CX4) and quasi-isotropic lay-up (CS2, CQ4). Testing series understudied with lay-up stacking sequence and woven fabric layers for each testing series is given with designation code as listed in Table 1. The designation code involves two alphanumeric characters and a number. The first alphanumeric character represents reinforcement weaving pattern, where C representing twill weave CFRP. Second alphanumeric character represents lay-up orientation sequences, where X, S and Q denotes cross-ply, symmetric and quasi-isotropic lay-ups. Others than cross-ply and quasi-isotropic lay-up, the other lay-up types are known as symmetric lay-ups comprised of woven fabric layers in only ±45˚ directions. However, symmetric lay-up is also classified as one of the quasi-isotropic lay-up types. The last number in the designation code represents the number of woven fabric layers in the respective series.

Table 1: Laminate lay-up, thickness and designation code

Lay-up type	Number of woven fabric plies	Stacking sequences	Designation codes
Cross-Ply	2	(0/90|90/0)	CX2
	4	(0/90|90/0)$_s$	CX4
Symmetric	2	(+45/-45|-45/+45)	CS2
Quasi-Isotropic	4	(0/90|+45/-45)$_s$	CQ4

*()$_s$: symmetric sequences with similar repetition of stacking sequences.

2.3. Mechanical testing

This section describes mechanical testing to determine in-plane modulus and elastic properties, independently material properties (i.e., unnotched strength and fracture energies) under investigation. The preparation prior to testing includes preparation of testing coupons (under remote tensile loading and associated strain measurements), the details and purpose of conducting these testing was described in Section 2.4. ASTM D 3039/D 3039M [7] was used as primary reference code of practice throughout mechanical testing conducted. All testing coupons were subjected under quasi-static loading condition using Universal Testing Machine (UTM) located at Structures Laboratory, Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia. The cross-head speed was kept constant at 0.5 mm/min and maximum load cell capacity of 50 kN was used. At least three coupons in each designed series were prepared and tested using UTM Machine to ensure the repeatability of composite coupons. If the standard deviation is found to be larger than 5%, additional coupons were tested thereafter. Testing coupons was elongated accordingly as remote tensile load was applied and load-displacement profiles were obtained from PC data-logger and recorded in every second interval. In current study, terminology "displacement" was used hereafter instead of "elongation" to give clarity for hybrid joint composite deformation.

2.4. Determination of elastic and material properties

Unnotched coupons testing in each designed series were carried out by using UTM Machine to determine independently elastic and material properties including Young's modulus, Ex, Poisson's ratio, υ_{xy}, shear modulus, G_{xy} and unnotched strength, σ_0. Unnotched coupons of 130 mm gauge length and 25 mm coupon width were prepared. Unnotched strength, σ_0 were recorded from UTM Machine data logger and Young's modulus, E_x was calculated by using dividing deviation in normal stress over normal strain from testing stress-strain profile. Poisson's ratio value was determined by applying bi-lateral strain gauges at the centerline of the tested coupon surface to obtain strain profile in both longitudinal and lateral directions. Tokyo Sokki Kenkyujo Co. Ltd. FLA-10-11 F series alloy foil strain gauge, with an active gauge length of 10 mm were bonded to the centerline of unnotched coupons using a cyanoacrylate adhesive. The strain gauges were posi-tioned orthogonally on CFRP unnotched coupons as illustrated in Figure 2.

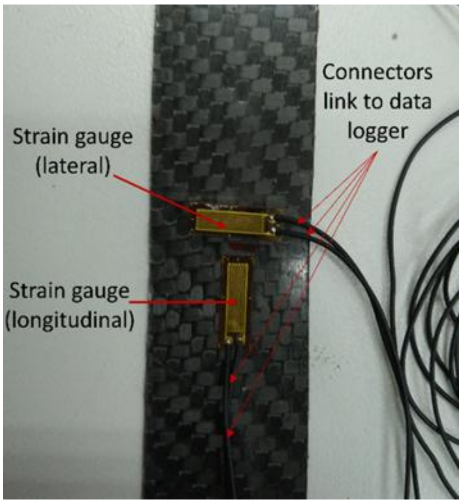


Fig. 2: Strain gauges was placed in both longitudinal and lateral direction connected to data logger

Strain increment profile datasets were recorded and extracted from UTM Machine data-logger in order to obtain longitudinal and lateral strains for Poisson's ratio calculations. Longitudinal and lateral strain was obtained from Equation 1 and 2 respectively.

$$\varepsilon_{lateral} = \varepsilon_x = (W_2-W_1)/W_1 \times 100\% \tag{1}$$

$$\varepsilon_{longitudinal} = \varepsilon_y = (L_2-L_1)/L_1 \times 100\% \tag{2}$$

$$\upsilon_{xy} = -\varepsilon_x/\varepsilon_y \tag{3}$$

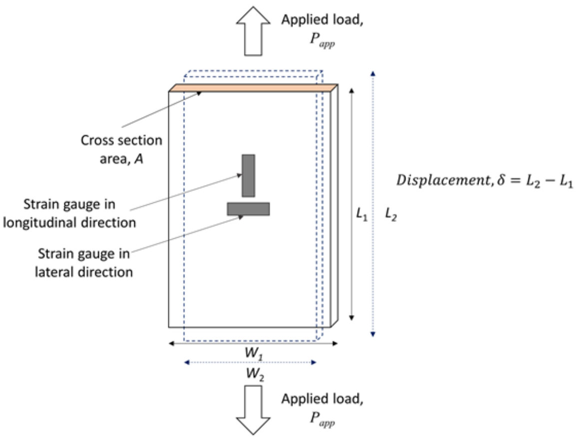


Fig. 3: Strain measurement as load applied by using strain gauge

As the load applied increased, deformation occurred in both orthogonal directions as shown in Figure 3 where elongation and shortening of unnotched coupon in longitudinal and lateral directions respectively. Poisson's ratio, υ_{xy} was calculated from Equation 3, taken between 0.05 % and 0.3 % strain interval as obtained from data-logger. Experimental set-up on strain measurement is shown in Figure 4 (a),

(b) and (c) whereby data logger was linked to biaxial strain gauges by connecting wires to record respective strains within specified time interval of the coupons tested.

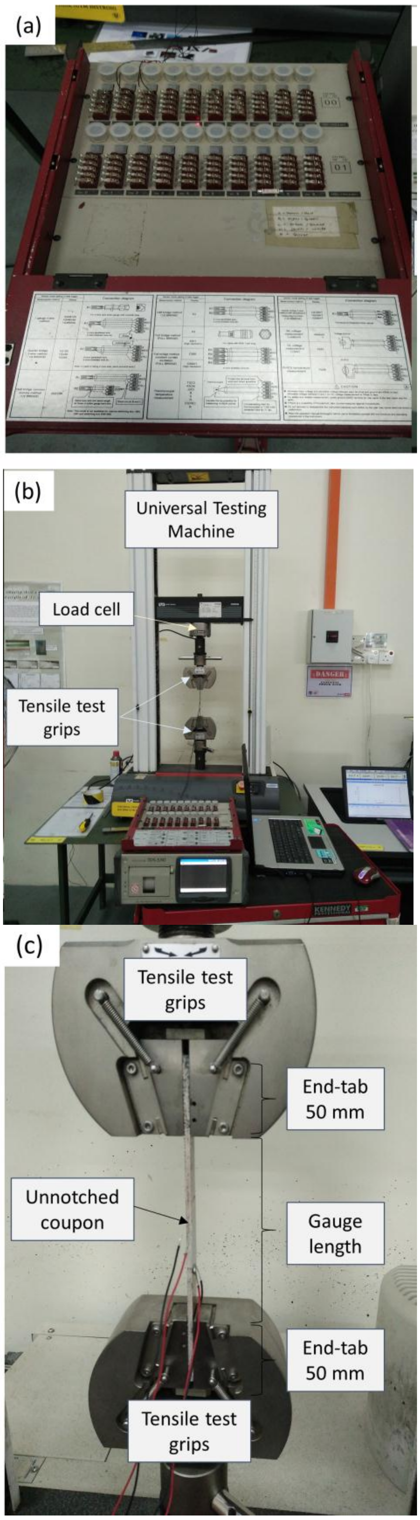


Fig. 4: (a) Data logger for strain gauge reading (b) UTM Machine tensile test set up connecting to data logger (c) unnotched coupon set up with strain gauges

Another independent elastic property to be determined was the shear modulus, G_{xy} of all testing series designation. Shear modulus was highly dependent upon nature of fiber orientation where cross-ply lay-up coupons were determined by testing unnotched coupons with diagonal cut at 45˚ to woven fiber orientation [8]. Similar procedures were implemented as discussed previously to determine Poisson’s ratio value where two strain gauges were positioned orthogonally. Maximum principle shear stress occurred at an angle of 45°, therefore this is regarded as the optimum angle of fibers to resist shear as it is placed diagonally. The strain values were recorded from the data logger and shear modulus was determined by Equation 4 (developed by Belmonte, 2002) where ε_y is longitudinal strain, ε_x is the lateral strain (obtained from data logger). In addition, σ_{app} is the applied stress at failure obtained from Equation 5 where P_{app} is applied load and A is the cross-section area by referring to Figure 2.

$$G_{xy} = \sigma_{app}/2(\varepsilon_y - \varepsilon_x) \quad (4)$$

$$\sigma_{app} = P_{app}/A \quad (5)$$

On the other hand, shear modulus for quasi-isotropic lay-up coupon was determined by using Equation 6 where E_x is Young modulus's and v_{xy} is Poisson's ratio obtained from associated unnotched coupon.

$$G_{xy} = E/2(1 + \upsilon_{xy}) \quad (6)$$

3. Results and discussion

3.1. In-plane elastic properties and unnotched strength determination

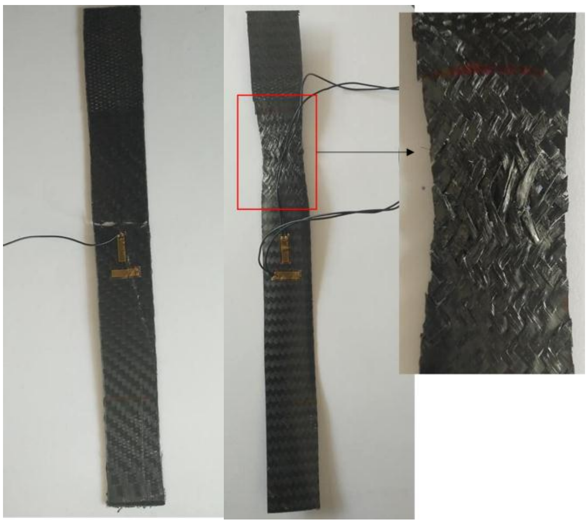
Elastic and material properties of composite coupons were carried out by testing unnotched coupon of all lay-up designations as specified in the testing series. At least three coupons were prepared for each laminate lay-up. The in-plane elastic properties were determined by using UTM Machine with a constant cross-head speed of 0.5 mm/min. The average measured properties, i.e., unnotched strength are given in Table 2. Young's modulus was taken within strain interval of 0.05 % and 0.3 % from respective stress-strain curve.

All tested unnotched coupons presented failure break within the gauge length. Due to no plate discontinuities, the coupons tend to break at the gripping region as it exhibited stress concentration at the edge grip. If this occurred the respective coupon has to be discarded and repeated until the coupon demonstrated failure within its gauge length. The final failure was found similar on all lay-ups (exceptional to CS2 lay-up) where the failure breaks within its gauge length as given in Figure 5 (a). However, CS2 lay-up coupons were twisted during testing as shown in Figure 5 (b) due to only ±45˚ ply exists to indicate weakness in tension (however ±45˚ lay-up promotes excellent resistance against shear).

Cross-ply coupon (CX2 and CX4 lay-up) shows larger failure load (correspondingly larger unnotched strength) than quasi-isotropic counterparts (CS2 and CQ4 lay-up) as listed in Table 2. This is due to larger volume fraction of 0˚ plies fiber direction in cross-ply lay-ups. As expected, presence of 0˚ plies as illustrated in Figure 6(a) able to sustain more applied load as most effective loading resistance angle as aligned to loading direction compared to the other fiber directions, similar findings were reported by Belmonte [8]. More inclination of fiber angle from loading direction (others than 0˚ fiber direction, e.g. 45˚) associated to lower resistance borne by intact reinforcing fibers.

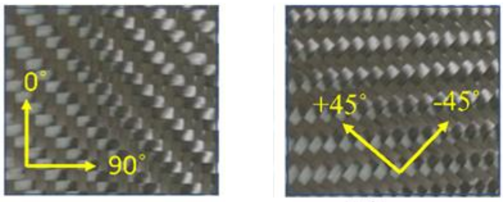
Table 2: Failure load and unnotched strength for CFRP lay-ups

Lay-up type	Laminate lay-up	Thickness, t (mm)	Failure load, P (N)	Unnotched strength, σ_0 (N/mm^2)	Mean unnotched strength, σ_0 (N/mm^2)
Cross-ply	CX2	0.423	5912	559	581 ± 19
		0.441	6681	606	
		0.432	6297	579	
	CX4	0.874	11261	515	488 ± 23
		0.851	9780	460	
		0.863	10521	488	
Quasi-isotropic	CS2	0.452	1251	111	114 ± 2
		0.429	1247	116	
		0.441	1249	115	
	CQ4	0.887	9760	440	441 ± 1
		0.856	9425	440	
		0.872	9593	441	



(a) Failure within gauge length (b) Fiber twisted within the coupon

Fig. 5: Failure occurred within gauge length on CFRP unnotched plates



(a) 0˚ plies (b) 45˚ plies

Fig. 6: Direction of fiber plies

Respective to coupon thickness, it was found that thicker coupons Respective to coupon thickness, it was found that thicker were stronger than thinner coupons counterparts due to better out-of-plane resistance throughout the coupon thickness. This is due to thicker coupon has more reinforcing layers and associated to higher delamination resistance. It was found that in spite of larger ultimate load in CX4 than CX2 lay-ups, but Young's modulus calculation in CX2 gives slightly higher modulus value than CX4 lay-up as shown in Figure 7. This is associated with lower deformation (or lower strain) in thinner coupons that promotes to more steep stress-strain curve. On the contrary, CS2 coupon gives lower Young's modulus compared to CQ4 lay-up due to CS2 lay-up comprised of only ±45˚ fiber direction to promote higher strain compared to equivalent cross-ply. In addition, CQ4 able to sustain higher stress due to present of 0˚ fiber orientation compared to CS2.

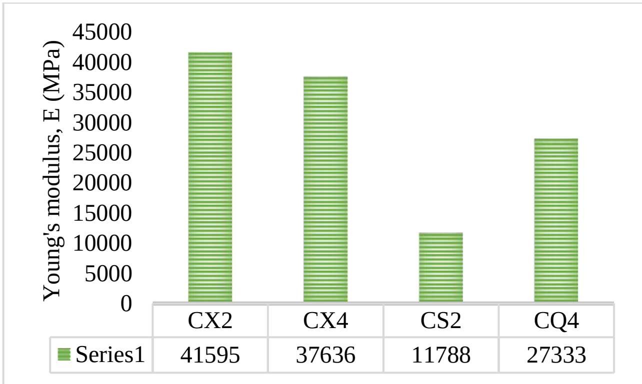


Fig. 7: Young's modulus for CFRP lay-ups

From the experimental datasets, quasi-isotropic lay-up has equivalent isotropic materials properties to give approximately isotropic Poisson's ratio of 0.308, closely findings reported by Belmonte [8]. As from Figure 8, CS2 lay-up showed higher Poisson's ratio due to higher strain in vertical direction due to existence of only ±45˚ fiber orientation which is prominent in resisting shear deformation. It was also found that lateral strain in ±45˚ ply is higher than 0˚ ply counterparts.

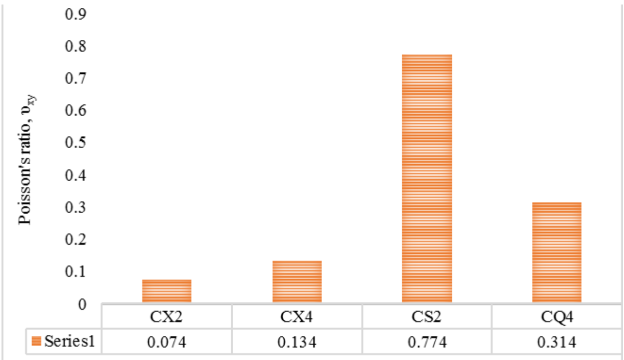


Fig. 8: Poisson's ratio for CFRP lay-ups

3.2. Shear modulus measurements

Separate unnotched coupons were prepared to determine shear modulus by referring to ASTM D 2344/D 2344M [9]. Strain measurement was recorded by using strain gauges, similar procedure with testing coupon preparations for Poisson's ratio as discussed earlier. Properties of shear modulus on woven laminate composite were dependent upon lay-up types. Figure 9 shows measured shear modulus in all lay-ups designation series. CFRP quasi-isotropic lay-up shows larger shear modulus than cross-ply lay-up due to presence of 45˚ plies in quasi-isotropic lay-up that able to resist higher shear deformation and increase the coupon shear rigidity, similar findings was reported by Belmonte [8]. From Figure 9, CQ4 lay-up shows highest shear modulus due to different lay-up orientation design on each layer where 0˚ plies lead to increase shear stress and ±45˚ plies resist shear deformation to increase respective coupons rigidity.

As cross-ply lay-up only consists of 0˚ and 90˚ plies and the stacking sequence of both lay-ups were oriented in similar fashion (due to similar warp and weft density), delamination failure tends to occur due to less resistance between each lay-up in composite coupon. In opposite, quasi-isotropic lay-up consists of ±45˚ plies where increased the resistance between each lay-up that caused less delamination failure compared to cross-ply lay-up. Although care has been made to avoid presence of voids within the composite panels but increasing number of woven fiber layers was found difficult to be fully absorbed by crimping fiber due to high viscosity of mixing binder system.

Porosity within composite coupons were less expected in large manufacturing sector practice but current work used hand lay-up fabrication technique in laboratory.

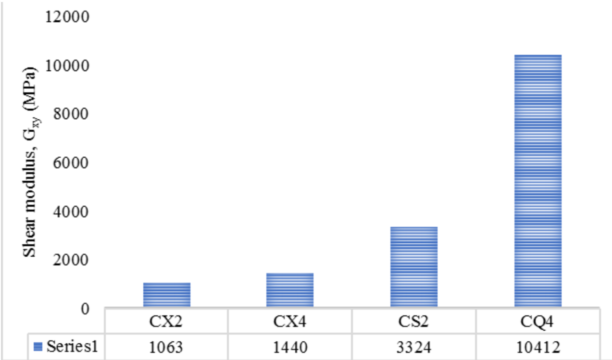


Fig. 9: Shear modulus for CFRP

4. Conclusion

All CFRP testing coupons demonstrates similar failure breaks within its gauge length except for CS2 testing coupon. CS2 coupons demonstrated twisting phenomena within the gauge length due to only ±45˚ ply exists to indicate weakness in tension. Moreover, CFRP cross-ply lay-up is found stronger than the quasi-isotropic lay-ups due to the more volume fraction of 0˚ fiber direction, but to the less extend in CFRP coupons due to low fiber volume fraction. Thicker coupon is more effective to transfer friction load through the coupon thickness than thinner coupons counterparts leading to larger failure load.

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