EXPERIMENTAL INVESTIGATION ON FLEXURAL BEHAVIOUR OF HYBRID UNIDIRECTIONAL FIBRE–REINFORCED POLYMER (FRP) COMPOSITES CONTAINING DIFFERENT GRADES OF CARBON FIBRE*)

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Abstract. *The objective of this work is to investigate the flexural behavior in terms of stress-strain response and failure mechanism of hybrid FRP composites containing the mixture of high strength carbon fibres and high modulus carbon fibres arranged in various stacking configurations. In addition to the variation in their stacking configurations, the span-to-depth ratio of the tested specimens was also varied. The specimens were cut from hybrid unidirectional FRP plates produced from unidirectional CFRP prepregs. The prepregs were produced from carbon fibre tows embedded in epoxy matrix. Flexural testing was carried out in accordance with ASTM D790 test standard in an INSTRON 5500R UTM equipped with a three-point bend test rig with adjustable span, such that the span-to-depth ratios can be controlled more accurately. The result showed that failure stress and failure strain were increase with the increase of span-to-depth ratio, but hybrid effect was not observed.*

Keywords: *hybrid CFRP composites, stacking configurations, flexural properties, span-to-depth ratios.*

INTRODUCTION

Superiority in specific mechanical properties of fiber-reinforced polymer (FRP) composites have lead to their widespread use in various fields such as aerospace [1], air, marine and ground transportations [2], construction and civil engineering [3] and leisure and sport [4]. Some of them are subjected to flexural loading, such as bridge beams and girders, yacht masts, aircraft wings, as well as helicopter and wind turbine rotor blades. Although CFRP composites are known to being more expensive in comparison to GFRP composites, lower density of typical carbon fiber, 1.80 $g{\cdot}cm^{-3}$ [5], compared to that of glass fiber, 2.58 $g{\cdot}cm^{-3}$ [6], would be an advantage for many applications where weight limit is a crucial issue [7].

Various properties of different hybrid fiber systems of FRP composites have been reported. For example, (i) tensile properties (*e.g.*, jute combined with chopped strand glass fiber mat, and short glass combined with short carbon fibers [8], (ii) compressive properties (*e.g.*, aramid combined with glass fibers, UHMPE combined with carbon fibers, and sisal fibers combined with chopped strand glass fibers mat [9-11]), (iii) flexural properties (*e.g.*, natural fibers combined with chopped strand glass fibers mat [12], and graphite combined with E-glass fibers [13]. However, published information concerning the improvement of flexural properties of hybrid FRP composite system containing different grades of carbon fiber has been very limited.

It was reported [14] that the flexural properties of unidirectional hybrid carbon/silicon carbide/epoxy FRP composites being considerably higher than those of the baseline CFRP composite with an increase of up to 22% in flexural strength being noted from the replacement of the top one C layer by stronger SiC in an eight-layer configuration. In light of the successful results obtained previously for hybrid CFRP composites, in this work the authors have investigated the flexural properties of CFRP composites in which a number of the top layer(s) being replaced with stronger and stiffer carbon fiber instead of silicon carbide fiber.

EXPERIMENTAL PROCEDURE

Carbon fibres being utilized in this work is a mixture of PYROFIL™ TR-50S [15] and HexTow™ IM7 [16] embedded in a common Kinetix® R240/H160 [17] epoxy matrix. Detail information of these constituent materials has been presented in Table 1.

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Table 1. Properties of constituent materials

Material	**Density** (g·cm^{-3})	**Filament dia.** (μm)	**Tensile**			**Compress-ive strength** (MPa)
			Strength (MPa)	**Modulus** (GPa)	**Failure strain** (%)	
PYROFIL™ TR-50S carbon fiber [15]	1.82	7	4900	240	2.0	
HexTow™ IM7-12000 carbon fiber [16]	1.78	5.2	5570	276	1.9	
Kinetix® R240/H160 epoxy [17]	1.09	N/A	83.3	3.65	9.8	98

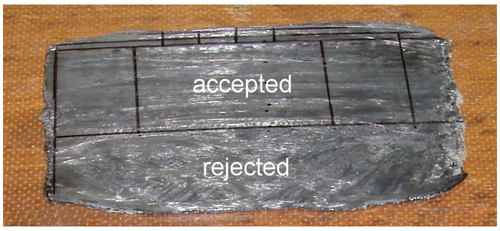


Fig 1. A hybrid CFRP plate

Specimen preparation. Specimens were cut from ~2-millimeter thick CFRP plates, Fig 1, using a diamond-tipped circular cutting machine rotated at ~10000 rpm. Before being measured, marked and recorded, both the longitudinal edges of each specimen were carefully polished to remove any possible edge damage due to cutting that may affect their mechanical properties under investigation. The three stacking configurations being produced were illustrated in Fig 2. Each layer in the figure represents a layer of prepreg sheet. Fabrication procedure of the prepregs and plates has been presented in details by the current authors in a published papers [5].

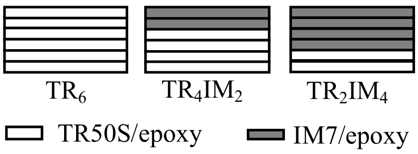
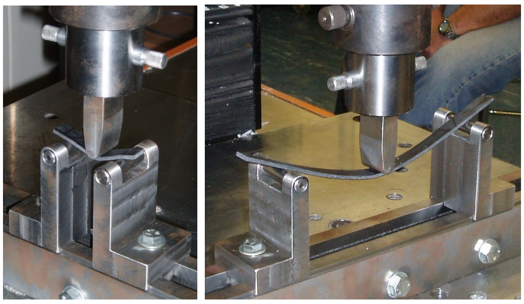


Fig 2. The stacking configurations

Flexural testing. Flexural testing was carried out in accordance with the ASTM D790 in an Instron® 5500R UTM. The specimen geometry was rectangular with a 12.7 mm width and thickness depending upon the thickness of their respective composite plate. Span-to-depth ratios, *S*/*d*, of 16 and 64 [14], were selected in the present work. For each case, at least five specimens were prepared and tested. The testing performance has been illustrated in Fig 3.



(a) *S*/*d* = 16 **(b)** *S*/*d* = 64

Fig 3. Flexural testing

RESULT AND DISCUSSION

Samples of the failed specimens have been depicted in Fig 4 below. Closer observation revealed that the shorter specimens, *S*/*d* = 16, had experienced shear failure in their middle inter-layers due to relatively higher shear stress in comparison with their respective normal stress, combined with low inter-laminar shear strength. Longer specimens, *S*/*d* = *64*, where normal stress was relatively higher in comparison with their respective shear strength had demonstrated flexural failure indicated with the presence of fiber-matrix interface debonding followed by fiber pull-out and fiber breakage.

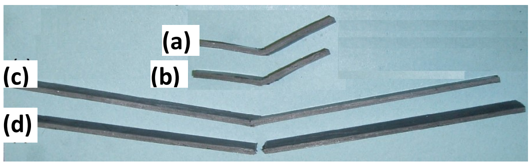


Fig 4. Samples of failed specimens: (a) and (b) Shorter specimens, *S*/*d* = 16, and (c) and (d) Longer specimens, *S*/*d* = 64.

Stress-strain responses have been presented in Fig 5. Different failure modes between short specimens, *S*/*d* = 16, and long specimens, *S*/*d* = 64, as has been previously discussed also supported by the σ–ε curves. Increase of strain without increase of stress representing the progress of interlaminar shear failure for most of the specimens being noticed in Figs 5(a), 5(c) and 5(e) on the left side was not observed in Figs 5(b), 5(d) and 5(f) on the right hand side. In addition, general trend being noticed in Fig 5 was longer specimens exhibited higher failure stress, but an increase of higher strength and higher modulus fiber content, both short and long beams, did not result in the increase of failure strength. In other words, hybrid effect was not observed.

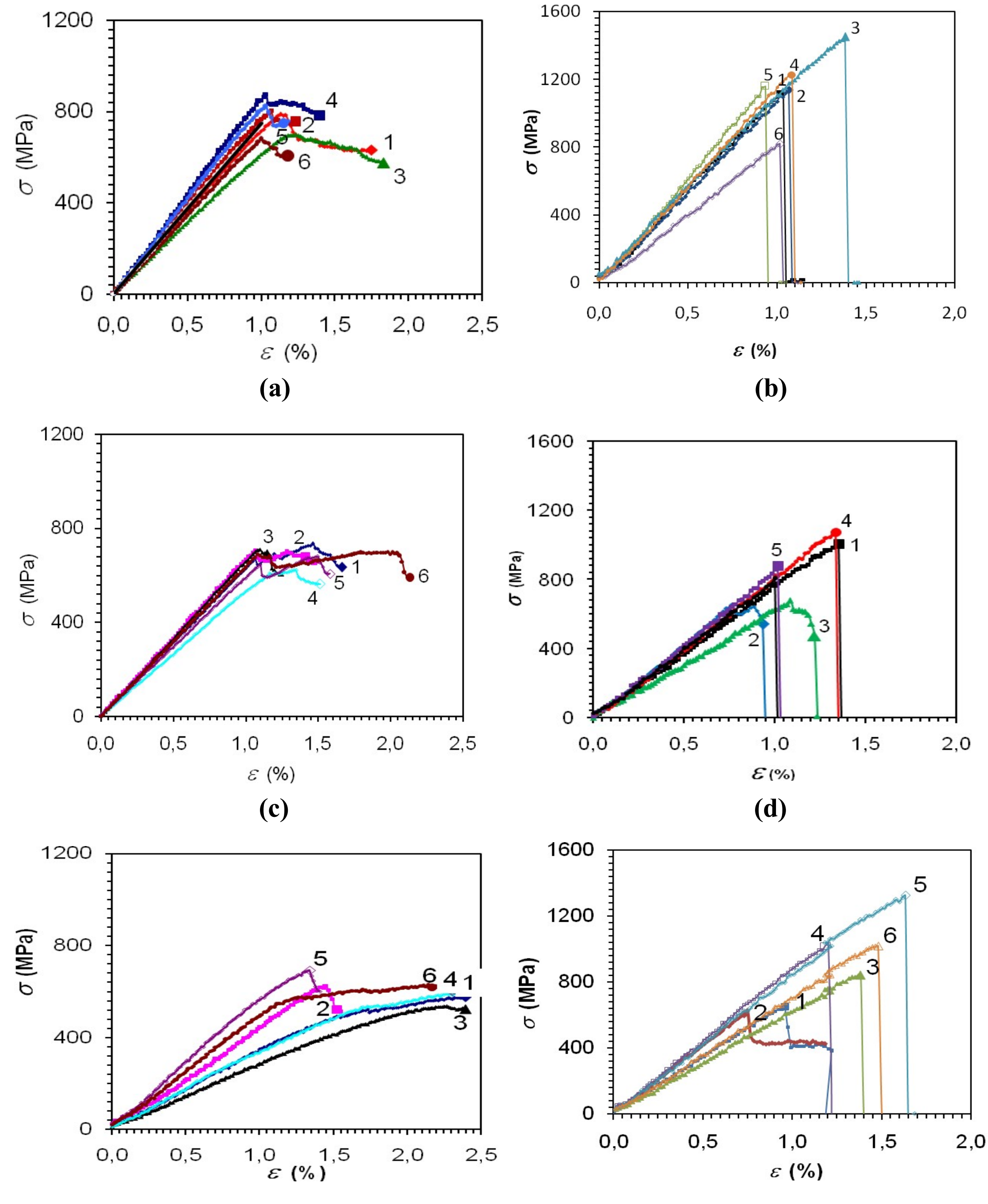


Fig 5. Load-crosshead displacement relations of the samples: (a) TR_6 at *S*/*d* = 16, (b) TR_6 at *S*/*d* = 64, (c) TR_4IM_2 at *S*/*d* = 16, (d) TR_4IM_2 at *S*/*d* = 64, (e) TR_2IM_4 at *S*/*d* = 16, (f) TR_2IM_4 at *S*/*d* = 64.

Short beams were generally produced higher failure strain. Higher shear-to-normal stress ratio, $\tau/\sigma = d/S$, accured in the neutral plane in comparison with that in the longer ones may be respionsible for short beams being fail by shear, as has been pointed out by Davies and Hamada [14].

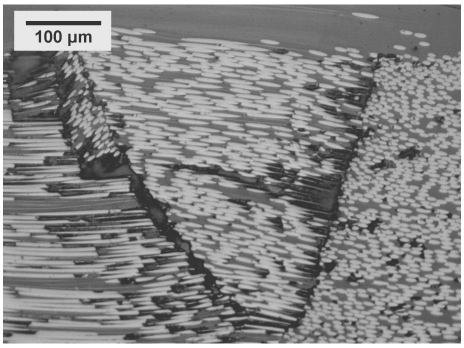


Fig 6. A typical fracture region of specimens tested at S/d = 64 showing fiber out-of-plane buckling and kinking domination in the compressive side.

Unlike those of short beams, the highest failure strains were observed to produce by specimens producing the highest failure stress. Considering failure was initiated at compressive side (Fig 6), these failure stresses and strains may be closely associated with the properties of the IM7-12000 fiber, *i.e*. the higher stress and higher modulus fiber.

CONCLUSION

Flexural behaviour of hybrid unidirectional fibre-reinforced polymer composites containing different grades of carbon fibre has experimentally been investigated. Hybrid effect was not observed by partial substitution of slightly higher strength and modulus fiber for the reference fiber. In the contrary, both failure stress and failure strain were found to increase with the increase of span-to-depth ratio.

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