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Hole Size Effects on the Open Hole Tensile Properties of Woven Kevlar-Glass Fibre Hybrid Composite Laminates

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ABSTRACT

The effects of hole size on open hole tensile properties of Kevlar-glass fibre hybrid composite laminates were thoroughly investigated in this work. Woven Kevlar/glass fibre epoxy composite laminates were fabricated using hand lay-up and vacuum bagging technique. Specimens of five different hole size (1 mm, 4 mm, 6 mm, 8 mm and 12 mm) were carefully prepared before the tensile test was performed according to ASTM D5766. Results indicated that hybridizing Kevlar to glass fibres improved tensile strength and failure strain of hybrid composite specimen. In addition, increasing the hole size reduced strength retention of the hybrid specimen from 96% for 1 mm hole size to 62% and 44% for 6 mm and 12 mm, respectively. Fractography analysis showed that several types of failure mechanisms were observed such as brittle failure, ductile failure, fibre breakage, delamination and fibre-matrix splitting. It is concluded that as hole size increased, failure behaviour changed from a matrix dominated failure mode to a fibre-dominated failure mode.

Keywords: Glass fibre, hole size, hybrid composites, Kevlar fibre, open hole tensile

INTRODUCTION

Over the past 40 years studies on the hole or notch strength of composite materials have been carried out extensively due to its importance to designers. Studies have been conducted experimentally, analytically or numerically on the effect of hole and hole size towards the strength of composite laminates loaded in tension, compression or bending by several researchers (Achard, Bouvet, Castanié, & Chirol, 2014; Balaco, 2000; Callus, 2007; Chen,Tay, Baiz, & Pinho, 2013; Erçin et al., 2013; Kannan, Wu, & Cheng, 2014; Green, Wisnom, & Hallett,

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2007; Higgins, Mccarthy, & Mccarthy, 2008; Salleh et al., 2013; Talib, Ramadhan, Rafie, & Zahari, 2013; Wisnom & Hallett, 2009; Yudhanto, Watanabe, Iwahori, & Hoshi, 2012; Zheng, Cheng, & Yasir, 2012). This is because, it is important for a designer to consider the effect of this hole on the strength of the laminate for safety purpose and efficient design. There are many factors that created sensitivity of a laminate to a hole such as size and thickness of the laminate, geometry and size of hole, orientation and thickness of ply, quality of machining process, and constituent of materials (Chen, Tay, Baiz, & Pinho, 2013; Kannan, Wu, & Cheng, 2014; Green, Wisnom, & Hallett, 2007; Wisnom & Hallett, 2009). In addition parametric effects of drilling conditions such as feed rate, spindle speed and drill point angle are also important because drilling operation can cause damage such as delamination and matrix cracking around the hole (Nasir, Azmi, & Khalil, 2015). All of these factors often affected and deteriorated the mechanical properties and performance of the composites by changing the extent of damage growth and propagation during loading.

Open hole strength is one of the factors that should be considered in component design as it can be a limiting factor during the application. Therefore, it is important to conduct open hole tensile test in order to determine the acceptable stress levels in the component design. Erçin et al. (2013) investigated the effects of hole size loaded in tension and compression under quasi-static loading of carbon fibre reinforced polymer (CFRP) composite laminates. From the results, the authors concluded that increasing the hole size from 3 mm to 7 mm caused tensile and compressive strength reduction. Furthermore, laminate lay-ups also affected the laminate strength. Laminate with maximum fibre orientation angle between adjacent plies has low tensile strength reduction that is 6.9% as compared to laminate with minimum fibre orientation angle between adjacent plies with 10.7%. Similar research were also conducted by Kannan, Wu and Cheng (2014) on flax yarn reinforced polypropylene (PP) laminates. In the study, the role of laminate lay-up, hole size and coupling agent on the composite laminates was investigated. Three laminate lay-ups namely axial, cross ply and off-axial were prepared with 4 mm hole size. Results indicated that the cross-ply laminate showed the highest strength retention that is 98% as compared to off-axial and axial laminates with 92% and 89%, respectively. The authors also confirmed that the strength retention of flax/PP specimen decreased as the hole sizes were increased. Uniaxial flax/PP specimen showed 89% strength retention for 4 mm hole sizes and around 78% strength retention for 8 mm hole sizes. The tensile strength of all laminates lay-up was found to improve with the usage of maleic anhydride grafted polypropylene (MAPP) copolymer film as coupling agent.

Salleh et al. (2013) in their study of kenaf/glass fibre composite specimens concluded that as the hole size increases from 1mm to 16mm in both kenaf composite and kenaf/glass fibre composite specimens, a significant decrement in tensile strength and tensile stiffness was observed. Kenaf composites and kenaf/glass fibre composites lost more than 59% and 54%, respectively of their tensile strength when the hole size was larger than 8 mm. However, hybridization of glass fibre to kenaf composite has significantly increased the tensile strength of the composite specimens. A report from Callus also stated that the value of tensile and compression strength and also strain-to-failure decreased significantly when the hole size increased for small holes and gradually decreased for larger holes. Green, Wisnom and Hallett (2007) also reported the influence of open hole size, ply and laminate thickness on the open hole tensile strength of quasi-isotropic CFRP composite laminates. The experimental investigation has confirmed that hole size and thickness are the factors that affect failure stress and mechanism. Their results showed that a maximum reduction of 64% in strength was observed when the specimen size was increased from 3.175 mm to 25.4 mm. However, for specimens with plies blocked together, the opposite trend of strength increasing with in-plane dimensions was observed. Three different failure mechanisms were observed namely brittle, pull out and delamination. Brittle happens when fibre failure occurs without extensive matrix damage while pull out occurs when there is extensive matrix damage such as delamination and matrix cracking existed.

In the present study, the effect of hole size on the open-hole tensile properties of interlaminated twill weave Kevlar-49/plain weave C-glass fibre hybrid composite laminates were investigated and evaluated. Specimens with six different hole size including unhole specimen were prepared in order to determine and compare the effect of hole size to tensile properties of pure and hybrid specimens. Further evaluation on tensile damage pattern was also performed to support tensile test results. This study is a continuation of a previous study done by Shaari, Jumahat, Abdullah and Hadderi (2015).

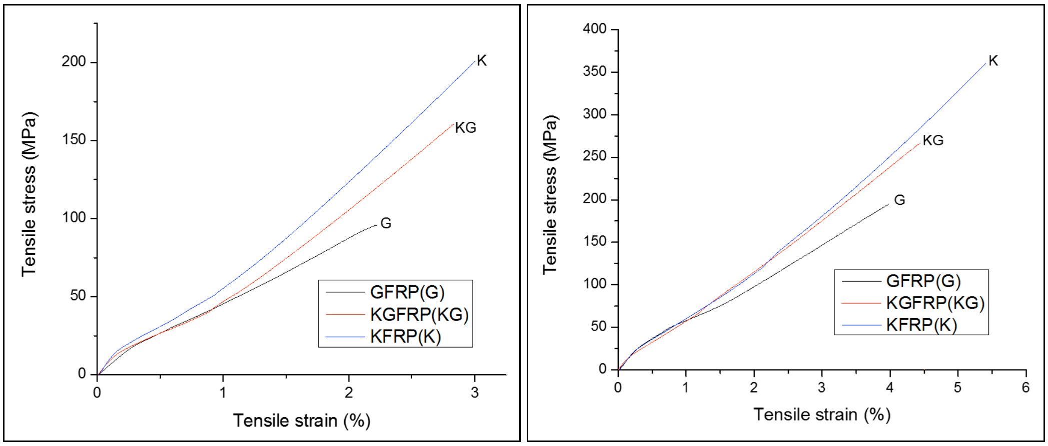
MATERIALS AND METHOD

In this study, composite laminates were fabricated using 2443 twill weave Kevlar-49 fibre and CWR200 plain weave C-glass fibre as the reinforcement materials while Miracast 1517 A/B epoxy resin system was used as the matrix material. An average of 2.5 mm specimen thickness of fibre reinforced polymer (FRP) composite laminates were developed and fabricated according to ASTM D5766.A mixture of epoxy resin and hardener with a ratio of 100:30 were prepared and applied to the fibres using hand lay-up followed by vacuum bagging methods. Three different composite systems were prepared namely glass fibre reinforced polymer (GFRP), Kevlar fibre reinforced polymer (KFRP) and Kevlar/glass fibre reinforced polymer (KGFRP). Hybrid specimen consists of 50% glass fibre and 50% Kevlar fibre with a stacking sequence of Kevlar fibre in the interior part while glass fibre in the exterior part (glass/Kevlar/glass). Laminate was vacuumed for one hour to remove air-trapped, bubbles and excess resin and left to cure at room temperature for 24 hours followed by post curing up to 120ºC for about 12 hours at 1ºC/min. Finally, specimens were cut using composite cutter before hole was drilled on the specimens using vertical drilling machine at a speed of 3000 rpm. It was very important to produce a good quality hole without any defects such as matrix cracking and edge delamination because the presence of such defects near hole region reduces the strength of a laminate.

Open hole tensile (OHT) test was performed to determine the damage tolerance of the damage composite specimens under tensile loading. A rectangular specimen with a dimension of 300 mm × 36 mm × 2.5 mm was prepared. Tabs are not required and generally not needed in hole specimen since the open hole acts as sufficient stress riser to force failure in the hole region. For hole specimen, five different hole size diameters (1 mm, 4 mm, 6 mm, 8 mm and 12 mm) were drilled on the specimen. Strain response was measured using 25 mm gauge length extensometer attached to the centre of the specimen. Testing was run using INSTRON 3382 Universal Testing Machine with crosshead speed of 2 mm/min. Tensile damage of composite specimens was captured using Canon A2200 digital camera to investigate the failure behaviour. The fractured surfaces of tested specimens were also observed using scanning electron microscope (SEM) model Hitachi TM 3000 table top microscope manufactured by Hitachi High Technologies, Japan.

RESULTS AND DISCUSSION

Results in Figure 1 shows the tensile stress – tensile strain behaviour of unhole and 6 mm hole of GFRP, KGFRP and KFRP composite specimen. From the results, it is confirmed that hybridization of Kevlar fibre to glass fibre has improved the tensile strength and tensile strain of the composite specimens. The result also indicates tensile strength of unhole GFRP specimen is 193 MPa while tensile strength of KGFRP is 267 MPa; an increment of about 38% with hybridization of 50% Kevlar fibre. Kevlar fibre is known as a ductile type fibre (Wan, Wang, He, Huang, & Jiang, 2007); therefore it has high tensile strain or elongation at break under tensile load when compared to glass fibre which has brittle type fracture behaviour. From Figure 1(a), GFRP and KGFRP is reported to have 4.1% and 4.4% of tensile strain indicating that hybridization also improved elongation at break and failure behaviour of the specimen. Fu et al. (2001), and Haery, Zahari, Kuntjoro and Taib (2012) also concluded that hybridization has improved the tensile strength of glass fibre composites. The presence of 6 mm hole has affected tensile strength and elongation at break of all composite specimens. Hole made to the specimens reduced the tensile strength and tensile strain of all specimens from 50-62% (Shaari,Jumahat, Abdullah, & Hadderi, 2015) and 54-64%, respectively. The result of reduction in tensile strength are expected as Saleh et al. (2016) have mentioned in their study that composite laminates usually demonstrated approximately 50% reduction in strength compared to their unhole strength.



(a) (b)

Figure 1. Tensile stress-strain of unmodified GFRP, KGFRP and KFRP of: (a) unhole specimen; and (b) 6 mm hole specimen

Ductile and brittle failure behaviour of Kevlar fibre and glass fibre are confirmed through SEM images as in Figure 2. It can be seen from both images that smooth surface in glass fibre indicates the brittle failure of glass fibre while the ductile Kevlar fibre tends to deform and has a higher strain under tensile load.

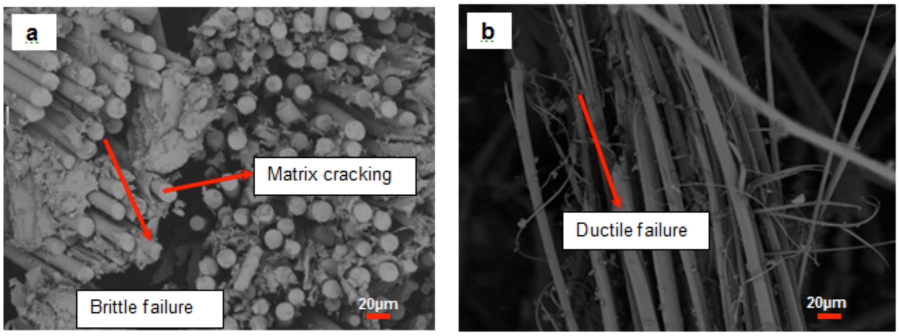


Figure 2. Tensile damage specimens of: (a) glass fibre; and (b) Kevlar fibre viewed under scanning electron microscope

Further investigation was carried out by comparing the effect of different hole size to composite laminates. The result in Figure 3 shows significant decrement in tensile strength of hybrid composite from 267 MPa to 165 MPa when the hole size increased from unhole to 6 mm and gradually decreased to 118 MPa when the size of the hole was further enlarged up to 12 mm in diameter. The hybrid composites retain about 62% of their tensile strength when the hole size was 6 mm. This is the highest strength retention obtained as compared to GFRP and KFRP specimens which have a much lower strength retention at the same hole size that is 50% and 57%, respectively. Table 1 displays the comparison of strength retention values for all specimens at all five different hole size. From the results, hybrid specimen exhibits the highest strength retention values at all five different hole sizes as compared to GFRP and KFRP specimens. At the largest hole size of 12 mm, KGFRP retains 44% of its strength while GFRP and KFRP only retain 39% of their strength. This confirmed the positive hybrid effect of the hybrid composite specimen. GFRP specimens lost 50% of its tensile strength when the hole size was 6 mm. Other research works also confirmed that larger hole size caused a decrement in tensile strength of the composites (Callus, 2007; Chen, Tay, Baiz, & Pinho, 2013; Erçin et al., 2013; Kannan, Wu, & Cheng, 2014; Green, Wisnom, & Hallett, 2007; Salleh et al., 2013). This is because, stress could be disseminated to a larger region of the specimen cross-section at small hole diameter whereas at larger hole size, the damage zone extended to greater portion of the specimen; therefore, less region remained to support the stress.

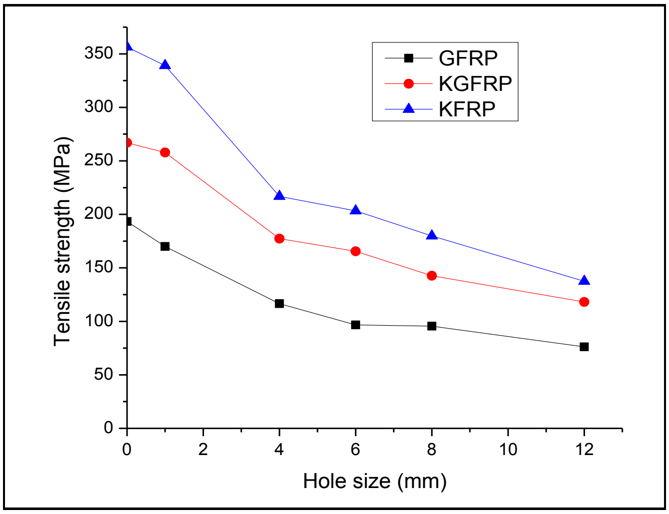


Figure 3. Tensile strength of unmodified GFRP, KGFRP and KFRP specimens with different hole size

Table 1
Open hole tensile strength and strength retention of GFRP, KGFRP and KFRP specimens

Tensile Properties/Hole Size		FRP Composite Specimen		
		GFRP	KGFRP	KFRP
Tensile strength (MPa)	Unhole	193.37±2.11	266.92±11.63	356.36±4.50
	1 mm	169.99±4.80	257.87±8.05	339.12±7.63
	4 mm	116.51±6.85	177.29±3.54	216.79±2.15
	6 mm	96.66±1.37	165.48±7.09	203.35±2.03
	8 mm	95.52±1.18	142.64±6.09	179.87±6.61
	12 mm	76.16±2.20	118.17±1.89	137.46±3.52
Strength retention (%)	1 mm	88	97	95
	4 mm	60	66	61
	6 mm	50	62	57
	8 mm	49	53	50
	12 mm	39	44	39

Macroscopic and microscopic observations of the fractured specimens were carried out to observe and analyse the tensile damage of the specimens. Specimens were viewed closely at the fractured area near the hole as in Figure 4, where it shows the tensile damage of specimens drilled with 6 mm hole. GFRP specimen (Figure 4(a)) displayed a brittle failure type in which the specimen was fractured and broken into two pieces. The specimen failure begins with fibre–matrix breakage at the open hole edge in the tensile loading direction. The damage extended into the entire fibre bundle around the hole and finally failed in brittle failure mode due to the brittle behaviour of glass fibre. The failure in KGFRP hybrid composite (Figure 4(b)) started with matrix cracking in resin-rich region followed by some fibre breakage. This is because, if hybrid composite is loaded in the fibre direction of tensile load, brittle fibre (glass fibre) will fail before ductile fibre (Kevlar fibre) (Swolfs, Gorbatikh, & Verpoest, 2014). Delamination area indicated with white appearance was seen around the open hole. Delamination is caused by cracked and fractured matrix which exposes the ply of glass fibres. This is the reason for the white appearance in the delamination area. This fracture behaviour can be taken as a warning sign before final failure. Meanwhile, Figure 4(c) shows ductile failure behaviour in KFRP specimen, where fibre–matrix splitting occurs at the open hole edge in the loading direction. However, due to ductile behaviour of Kevlar fibre, some of the Kevlar fibres only elongate without breaking.

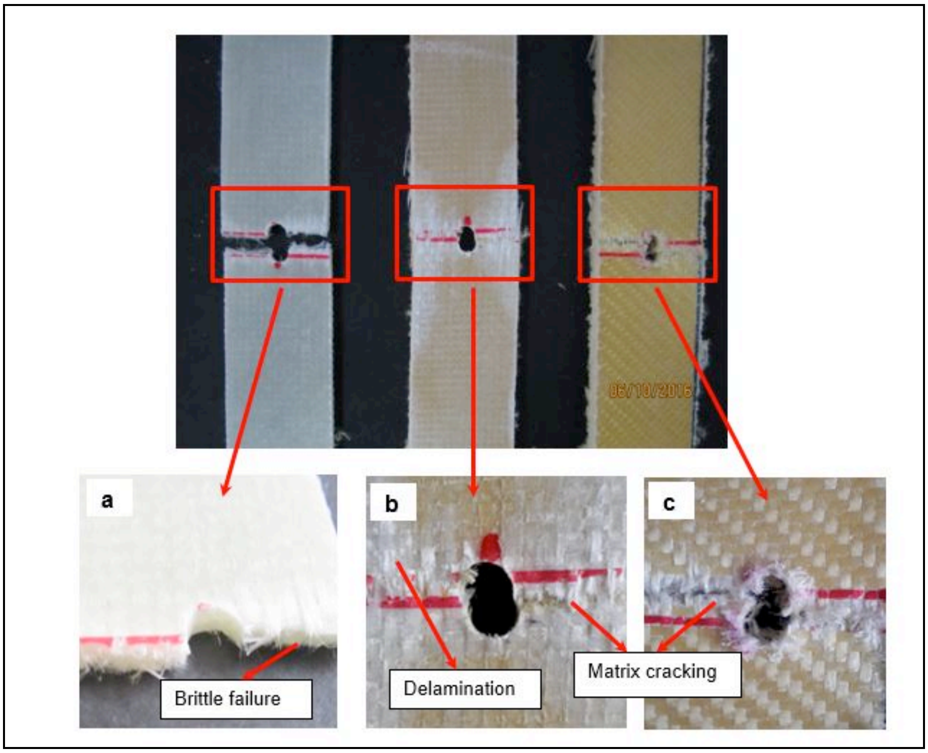


Figure 4. Tensile damage of 6 mm hole size specimens of (a) GFRP; (b) KGFRP; and (c) KFRP

Figure 5 shows tensile damage specimens of KGFRP composite laminates with various hole sizes ranging from 0 mm to 12 mm. The presence of hole acts as a stress riser in the specimen that caused the fibres near the hole edges started to fail. The higher stress near to this hole would lead the fibres to fail first. The failure mechanisms started with matrix cracking followed by delamination and fibre separation or breakage. Delamination area, which is indicated with white appearance near the open-hole region shows a reduction in area from unhole specimen to 12 mm hole size specimen. It can be concluded that for a specimen with small hole size, more loads are required to be applied before failure can occur. As the hole size increases, it acts as a stress riser, resulting in less load required for the specimen to fail. Therefore, less matrix cracking, delamination area and fibre breakage exist. The failure behaviour changed from a matrix-dominated to a fibre-dominated failure with the increasing of hole size. Similar observations were reported by Green, Wisnom and Hallett (2007) and Lagace (1986) in their studies. This phenomenon occurred due to the interlaminar stresses around the hole boundary; which decreases in importance with the increase of hole size.

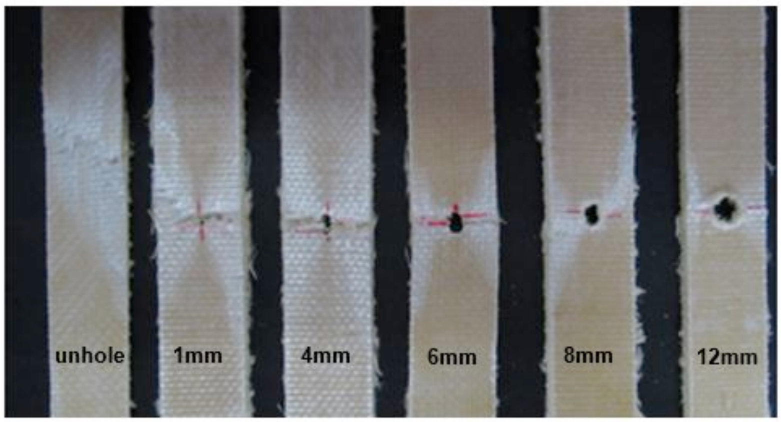


Figure 5. Tensile damage of KGFRP specimen with hole size diameter range from 0 mm to 12 mm

CONCLUSION

Open hole tensile test was successfully performed on Kevlar/glass fibre composite laminates according to ASTM D5766 with five different hole size. Experimental results concluded that strength retention decreased with the increase of hole size in all GFRP, KGFRP and KFRP specimens, in which KGFRP specimen holds the highest strength retention. Analysis of tensile damage showed that delamination was obviously seen in KGFRP specimens indicated with white appearance. As the hole size increased, the delamination area was observed to decrease. This is caused by the hole size that acted as the sufficient stress riser; therefore, the damage initiated near the hole edge.

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