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Comparison of Tensile and Compressive Characteristics of Intra/Interply Hybrid Laminates Reinforced High-Density Flexible Foam Composites

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ABSTRACT: The current study focused on fabrication and mechanical evaluation of intra/interply hybrid laminates–reinforced high-density flexible foam composites. The effects of composite thickness and expansion factor on the tensile and compressive characterization of the hybrid-laminated composites were experimentally investigated. Double face sheets were made of high-strength intra/interply hybrid laminates containing recycled Kevlar nonwovens and glass woven fabric. The results revealed that the hybrid laminates face sheet apparently promoted the tensile strength and tear resistance of the high-density flexible polyurethane foam. Tearing resistance in perpendicular direction exceeded more than twice the value in parallel direction. In terms of dynamic cushioning properties, cushioning force increased with the increase in composite thickness and the decrease in expansion factor, whereas the cushioning capacity loss, however, showed a different trend with the variation of the parameters. Most samples buffered more than 95% incident force under dynamic loading. Composite thickness and expansion factor exhibited significant influence on compression and indentation properties, including hardness, initial hardness factor, and indentation modulus. Except the composites with 10 mm thickness, the intra/interply hybrid laminated composites exhibited hysteresis loss of indentation force deflection ranging from approximately 30 to 38%, which was due to the fiber and thermal bonding point failure of hybrid laminates as unrecoverable damage. © 2014 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2015**, *132*, 41438.

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INTRODUCTION

Sandwich structural composites with face sheets are extensively used in numerous industrial applications like aerospace, automobile, and building for their excellent properties of high strength, modulus, stiffness, thermal insulation, acoustic absorption, cushioning, energy management, and ease of manufacturing.[1–8] Materials and structure selections of the face sheet and core are depending on the requirements of applications. Polymeric foams present excellent properties in chemical corrosion resistance, light weight, ease of machining, cushioning and energy absorption but also have several disadvantages such as low tensile and tearing strength and damage propagation.[9] To overcome the aforementioned drawbacks, polymeric foams are commonly combined with reinforcement to process into sandwich structure in various forms. Previous research reported that micro/nano fillers could enhance the impact resistance, cushioning, and compressive properties of polymeric foam–based composites.[10–14] Gharehbaghi et al.[15,16] found expandable graphite and melamine fillers contributed to the influence on flame retardance, tearing, and compressive properties of flexible polyurethane foam.

Efforts had been made on reinforcing the foam-based composites by embedding rigid cores with diverse structures, such as honeycomb beam, corrugated core, and egg-box sandwich structures under quasi-static compressive and dynamic loading.[17–19] Stitching process was also confirmed to strengthen the mechanical

Table I. Specifications of Foam-Based Hybrid Composites

Sample code	Composite thickness (mm)	Expansion factor	Foam density (kg/m^3)	Fiber volume fraction (%)
TH10	10 ± 1.10	3	333 ± 21	7.73
TH20	20 ± 0.06	3	333 ± 5.8	3.93
TH30	30 ± 0.07	3	333 ± 4.5	2.58
EF2	20 ± 1.05	2	500 ± 7.6	3.92
EF3	20 ± 0.06	3	333 ± 5.8	3.93
EF4	20 ± 0.30	4	250 ± 8.6	3.98
EF5	20 ± 0.25	5	200 ± 12	3.91

Expansion Factor was calculated by dividing volume of foam (m^3) by volume of mixture (m^3).

properties.[20–22] Numerous publications concentrated on function and effects of face sheet on foam-based composites. [20,23,24] Textiles that are made of high-performance fiber with various constructions involving woven, nonwoven, knitted, and unidirectional structures are commonly used as face sheet to meet the requirements in applications. [14,20,22–24] Hybrid laminates can integrate the advantages of different structures that are classified into five main categories in accordance with the way the constituents are mixed[25,26]: (a) interply hybrid laminates which combine two or more homogeneous reinforcing plies stacked in various sequences; (b) intraply hybrid laminates which are composed of different fibers in the same ply; (c) intimately mixed hybrids which the consistent fibers are mixed as randomly as possible without concentrations of either type existing in the materials; (d) selective placement in which the fibers are reinforcing the selected place where additional strength is needed; (e) superhybrid composites which consist of metal foils or composite plies stacked in specified sequences. In this study, we combine the two main structures intraply and interply hybrid to fabricate intra/interply hybrid laminates based on high-performance fibers as the face sheets.

Quasi-static compressive and dynamic loading resistance properties investigations on low-density flexible foam-based composites were reported in many articles,[15,16,19,27] whereas investigation on high-density flexible foam–based composites were extremely rare. Zaretsky et al.[28] studied planar impact response of high-density flexible polyurethane foam. But few literatures are published on mechanical properties of high-density flexible foam-based sandwich composites.

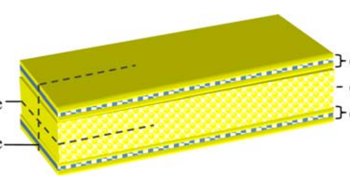

Figure 1. Schematic diagram of tearing test specimen of hybrid composites in parallel and perpendicular directions. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

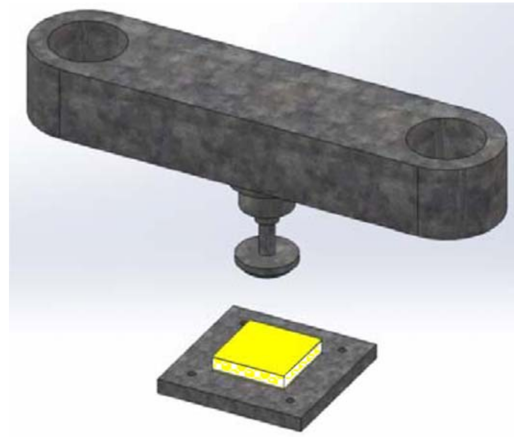

Figure 2. Drop weight cushioning instrument. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

The current study aims to experimentally investigate tensile and compressive properties of in intra/interply hybrid laminates reinforced high-density flexible foam composites. Recycled Kevlar nonwovens and glass woven fabric were laminated to form intra/interply hybrid laminates face sheet and high-density flexible foam with various thicknesses and expansion factors was fabricated as core. Influence of the variations on tensile and compressive properties, including tensile strength, tearing strength, delamination resistance, dynamic cushioning capacity, compression and indentation properties and hysteresis loss (HL), were investigated.

EXPERIMENTAL

Materials

Biocomponent polyester staple fiber (LMPET, purchased from Far Eastern Textile, Taiwan) had sheath-core structure. The core was composed of normal polyester and the sheath was low-melting point polyester with a melting point of 170°C. Para-aramid staple fibers were made of recycled unidirectional selvages consisting of 2820 D K129, 1000 D K29, and 2160 D K49 Kevlar multifilaments in lengths of 50–60 mm (DuPont Company, USA). Recycled Kevlar has high tensile and shear resistance and was used to reinforce the composites structure. E-glass plain woven fabric (Jinsor-Tech Industrial, Taiwan) was interlaced by 1100 D glass filaments with 34 ends and 26 picks per inch. Two-component flexible polyurethane foam was manufactured with polyether polyol and hardener. The hardener was a mixture of toluene diisocyanate and polymeric methylene diphenyl diisocyanate at a weight ratio of 80/20 (KLS Corporation, Taiwan).

Composites Preparation

The intra/interply hybrid laminates were composed of double intraply hybrid nonwovens with an interlayer of E-glass fabric. Recycled Kevlar/LMPET hybrid nonwoven was fabricated through blending, carding, lapping, and needle-punching process. Mechanical properties of nonwovens with various blending ratio had been studied in our previous work and 15 : 85 was considered as the optimum blending ratio to be applied in this study.[29] Double layers of Kevlar/LMPET hybrid nonwovens and

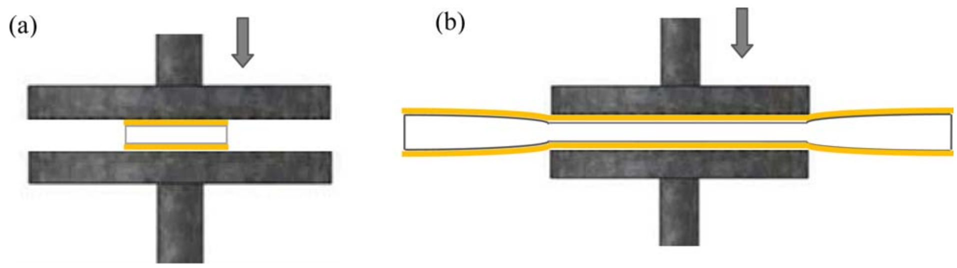

Figure 3. Schematic compressive test of (a) CFD and (b) IFD. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

an E-glass woven fabric were stacked and incorporated by needle-punching at 100 strokes/min. Thermal treatment in 180°C oven for 15 min melt the low-melting point component, generating thermal binding points between fibers to reinforce the laminates.

Polyether polyol and hardener were mixed in a weight ratio of 4 : 1 for complete cross-linking reaction. Hybrid laminates were pre-paved on top and bottom of the aluminum mold before the gel mixture being infused in. Then, the mold was sealed for foaming and expanding. The hybrid-laminated composites panels were manufactured with four different expansion factors ranging from 2 to 5 (EF2, EF3, EF4, and EF5) and different composite thicknesses varying from 10 to 30 mm (TH10, TH20, and TH30, controlled by dimension of the aluminum mold). The specifications of hybrid-laminated composites were tabulated in Table I.

Testing

Tensile Strength. Tensile test was performed using Instron 5566 test system. Specimen dimension and test procedure were determined in accordance with ASTM D3574-E. Place the dumbbell shape composites specimen in the grips with a 62.5-mm separation. An overhead speed of 500 ± 50 mm/min was set to test the stress until the composites totally rupture. Six specimens were measured in each type of composites.

Tear Resistance. The tear test specimen was trimmed into 152.4 mm × 25.4 mm dimensions. Specimen was pre-cut with 40 mm on one side of the specimen. Then, separate the block and fix each tab on each clamp. Crosshead speed of upper clamp was set at 500 ± 50 mm/min. Tear resistances in parallel and perpendicular directions, as shown in Figure 1, were both measured in all the foam-based hybrid composites. Six specimens were evaluated in each type of composites.

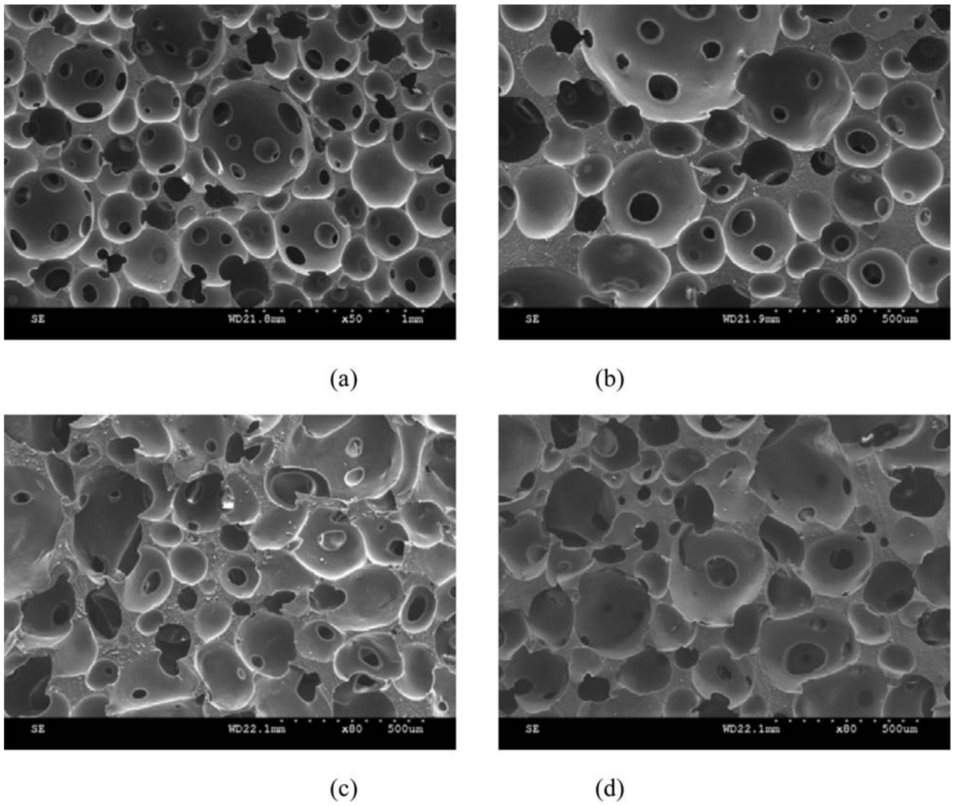

Figure 4. SEM micrographs of PU foam core with expansion factors of (a) 2, (b) 3, (c) 4, and (d)5.

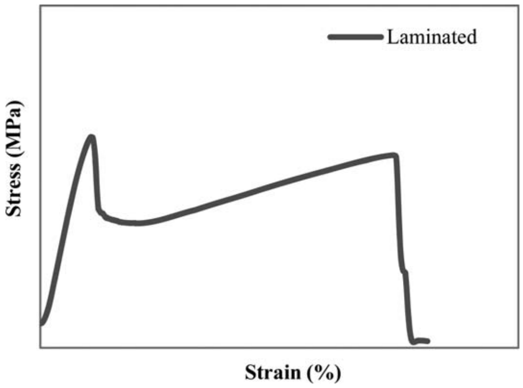

Figure 5. Typical tensile curve of hybrid-laminated composites.

Delamination Resistance. Delamination resistance test of hybrid laminates cover ply was conducted by Instron 5566 according to ASTM D3936. Samples had nominal dimensions of 75 mm × 150 mm with a 38-mm pre-separation between the surface nonwoven fabric and the rest part. Two parts were clamped by the upper and lower clamps, respectively, being separated at a crosshead speed of 304 ± 10 mm/min. Delamination resistance was determined by average peak force divided by width. Eight specimens were measured in each type of composites.

Cushioning Capacity. Localized dynamic cushioning test was performed by a drop weight testing instrument equipped with an impulse data acquisition system (Kuang-Neng Machine Factory, Taiwan) (Figure 2). The hybrid composites specimen (100 × 100 mm^2) was positioned on the bottom platform with a load cell fixed in the center. A 9.4-kg hemispherical-end drop weight impactor dropped from approximately 65 mm high with an incident force of 9.0 kN. A specimen was impacted for six times at 60 s intervals and residual force of every impact was recorded. Load loss, F_c, or cushioning force, is determined by using eq. (1).

$$F_c = F_i - F_r \quad (1)$$

where F_i is incident force and F_r is the residual force within the impact time interval. Cushioning capacity loss (CCL) was also calculated of every impact to evaluate the loss of cushioning capacity. CCL was defined as the percentage difference between the load loss F_c and the initial one:

$$CCL_{(n)} = \frac{F_{c\ (1)} - F_{c\ (n)}}{F_{c(n)}} \times 100 \ (n \geq 2) \quad (2)$$

where $F_{c\ (n)}$ is load loss and $F_{c\ (1)}$ is the initial load loss.

Compressive Properties. Compression force deflection (CFD) and indentation force deflection (IFD) are primary parameters to evaluate flatwise compressive properties of foam-based materials. Both of CFD and IFD were measured by Instron 5566 in accordance to ASTM D3574 (Figure 3). A 50 mm ×50 mm composite specimen was placed on the platform. A circular pressure foot with a 200-mm diameter compressed the specimen at a constant speed of 50 ± 5 mm/min. CFD value was defined as follows:

$$CFD = \frac{F_{cf}}{A} \quad (3)$$

where F_{cf} is the contact force and A is the specimen area. Hardness was determined as indentation force when the sample was compressed to 50% of this initial thickness. IFD values are dependent on specimen dimensions and all the composites were trimmed as 300 mm ×300 mm. Value of IFD was recorded after maintaining the deflection for 60 ± 3 s. Initial hardness factor (IHF) was defined as the ratio of 25% IFD to 5% IFD and indentation modulus (IM) was calculated using the following equation:

$$\mathrm{IM} = \frac{40\%IFD - 20\%IFD}{20\%\ IFD} \quad (4)$$

where 20% IFD and 40% IFD were indentation forces at 20 and 40% deflections, respectively. Hysteresis exhibited in all compressive tests because of energy loss. HL measured the difference in energy between loading and unloading, as shown in eq. (5):

$$Hysteresis\ \ loss = \frac{E - E_{RT}}{E_{RT}} \times 100 \quad (5)$$

where E is the loading energy and E_{RT} is unloading energy. Hysteresis loss of CFD (CHF-HL) and IFD (IFD-HL) were measured by compressing the sample by 65 and 25% of their initial thickness, respectively. Eight specimens were tested for each test of each type of composites.

RESULTS AND DISCUSSION

The microstructure of high-density flexible polyurethane foam core with various expansion factors ranging from 2 to 5 are shown in Figure 4(a–d). Porosity samples showed an open cell

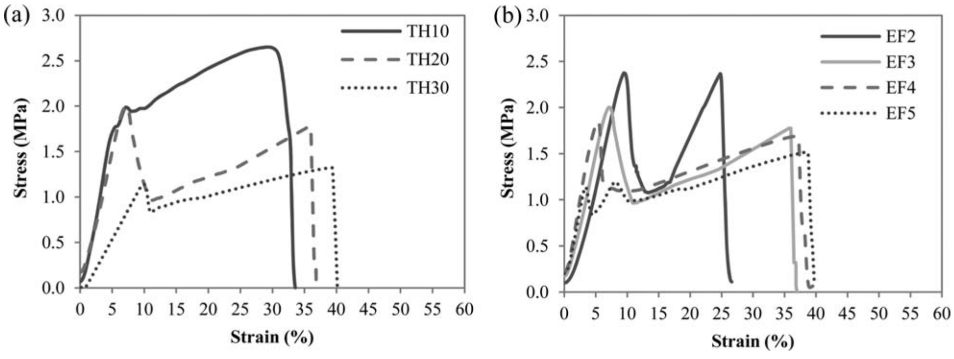

Figure 6. Tensile behavior of hybrid composites with various (a) panel thicknesses and (b) expansion factors.

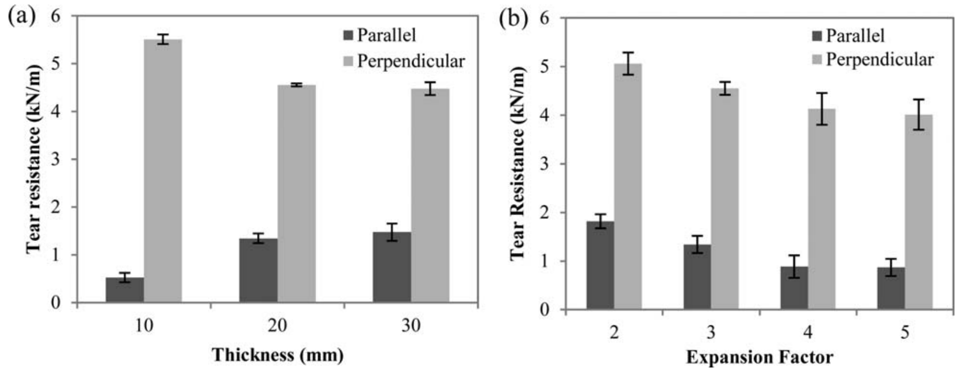

Figure 7. Parallel and perpendicular tear resistance of hybrid composites with various (a) panel thicknesses and (b) expansion factors.

configuration and cell strut accounted for a large proportion of volume. Samples with expansion factors of 2 and 3 showed spherical cell configuration with nearly uniform distribution. Samples of 4 and 5 expansion factors showed irregular cell shape and cell strut, which were generated by nonuniform pressure during expanding and foaming.

Tensile Strength

Typical tensile curves of hybrid-laminated composites are presented in Figure 5. Because glass fiber has high modulus and low elongation, tensile stress of hybrid-laminated composites increased initially with a steep slope to reach the fracture threshold of glass fiber at small strain. After the first peak load, the composites panel continued to be elongated and totally break at the second peak load. The elongation at break of hybrid-laminated composites was low because the hybrid laminates reinforced and restricted the high-density flexible foam to rupture at high strength and low elasticity. Therefore, intra/interply hybrid laminates can reinforce the flexible foam composites panel at both initial strain and final strain resulting two load peaks, respectively.

Figure 6 presents the tensile behavior of hybrid composites with various thicknesses. All hybrid laminated composites with various composite thicknesses exhibited high tensile strength, which meant the second peak load [Figure 6(a)]. With the composite thickness increasing from 10 to 30 mm, the tensile strength of the hybrid composites decreased from 2.88 to 1.48 MPa, which is because of the decreasing fiber volume fraction. According to our design, composite samples with various thicknesses have identical face sheets. With the thickness of the composites increasing, foam volume fraction increased, whereas fiber volume fraction decreased. Because the reinforcing fibers dominantly affect the tensile strength of the composites in longitudinal direction, the tensile strength decreased with the increase in composite thickness.

Figure 6(b) illustrates the effects of expansion factor on tensile testing results of hybrid-laminated composites. Double peak load both decreased and strain of tensile strength was also extended with the expansion factor increasing from 2 to 5. There are two main reasons: first, more foam ruptured with foam density increasing from 200 to 500 kg/m^3 as expansion factor decreased from 5 to 2; second, adhesion strength between laminates and foam was also influenced with contact surface which was increased with increasing foam density. The interlaminar strength and reinforcement restriction was also enhanced so that the composites broke at high strain with low adhesion restriction.

Tear Resistance

Tear resistance on parallel and perpendicular directions of flexible foam–based hybrid composites are shown in Figure 7. One of the main concerns was that tear resistance in perpendicular

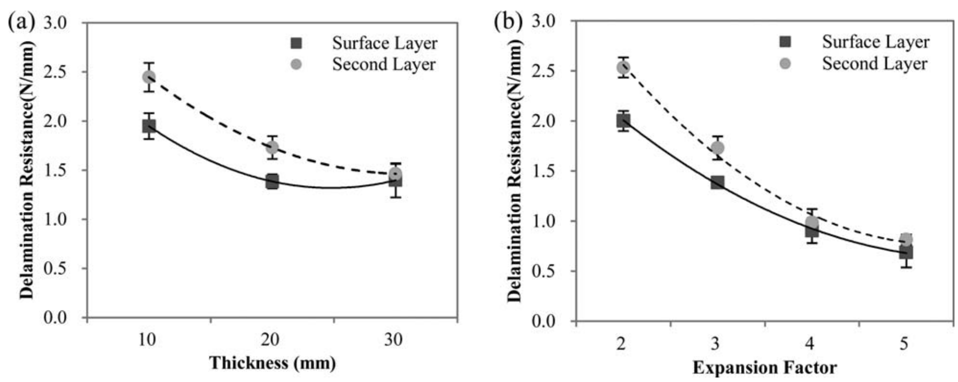

Figure 8. Delamination resistance of hybrid-laminated composites with various (a) composite thicknesses and (b) expansion factors.

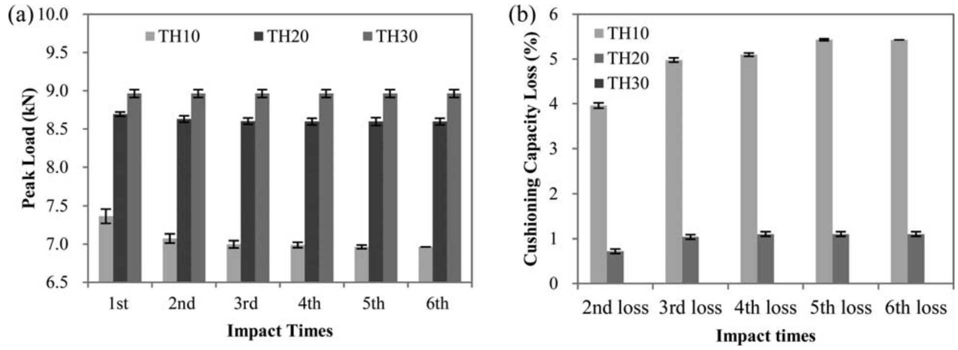

Figure 9. Effects of panel thickness on (a) cushioning force and (b) CLL of hybrid composites.

direction was always higher than in parallel direction because the foam was reinforced with high-strength hybrid laminates transversely. The differences between perpendicular and parallel tear resistances of hybrid-laminated composites were at large ratio, which were 953, 239, and 203%, because the hybrid laminates had high tensile and tear strength based on the high performance fibers. Effects of composite thickness on parallel and perpendicular tear resistance exhibits different tendencies because the bending strength was enhanced with increasing thickness in relation to parallel tear resistance. As the main failure mechanism was rupture of cell wall, tear resistances in two directions both declined linearly with foam density decreasing from 500 to 200 kg/m^3. Direction factor influenced evenly on every group of composites, thus the difference between parallel and perpendicular tear resistances was equal in every sample with different expansion factor.

Delamination Resistance

Delamination test was conducted to evaluate the interlaminar strength of the hybrid laminates. The laminates structure is formed based on three main factors: friction between entangled fibers, which is attributed to needle punching process; bonding force of bonding points, which is generated through thermal treatment; and adhesion force, which depends on the expansion force to immerse the fibers and the stickness of the foam. In this study, delamination resistance of the surface layer and the second layer of the intra/interply hybrid laminates were both studied.

Figure 8(a) depicts the delamination behavior of hybrid-laminated composites with same expansion factor but various composite thicknesses. The value of surface layer was always lower than the second layer because the second layer was located closer to the foam core and saturated more completely. With the increase in composite thickness, delamination resistance exhibited a downtrend and then became moderate because the bending strength influenced the precise of the test. The delamination resistance of the double layers both declined steadily with the increase of expansion factor. The main reason was that high expansion factor caused low expansion force during foaming process. Foam saturated the hybrid laminates and the contact area between foam and fibers decreased with the reduction of foam density.

Cushioning Capacity

Cushioning force and CCL estimated the cushioning capacity and durability of the hybrid-laminated composites under multi-localized low-velocity impacts. In every impact, cushioning force of hybrid-laminated composites of TH10, TH20, and TH30 showed an increasing trend with increasing composite thickness because more volume of cell collapse to absorb incident energy [Figure 9(a)]. TH30 sample buffered more than 98.9% incident force even in the sixth impact. The CLL values of TH10 and TH20 for every impact were presented high because that the impact damage types of hybrid laminates were almost fracture and debonding, which were unrecoverable [Figure 9(b)]. Meanwhile, TH30 exhibited tiny CLL value in every impact time because the panel was thick enough to prevent the propagation of impact wave.

Figure 10(a) illustrates the cushioning property of hybrid composites with various expansion factors. It is worth noting that

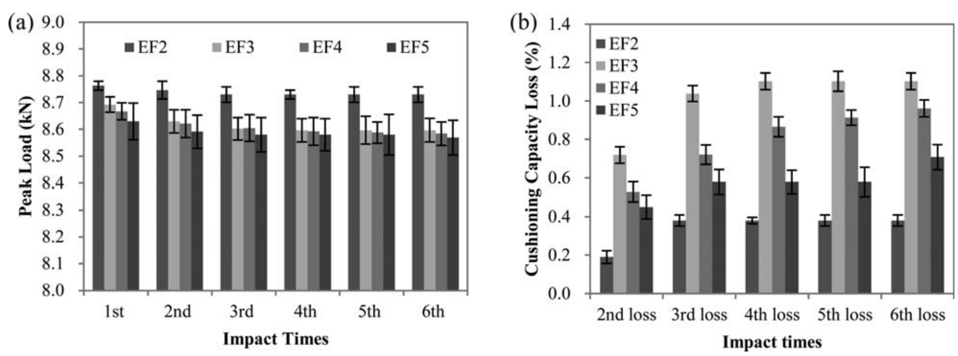

Figure 10. Effects of expansion factor on (a) cushioning force and (b) CLL of hybrid composites.

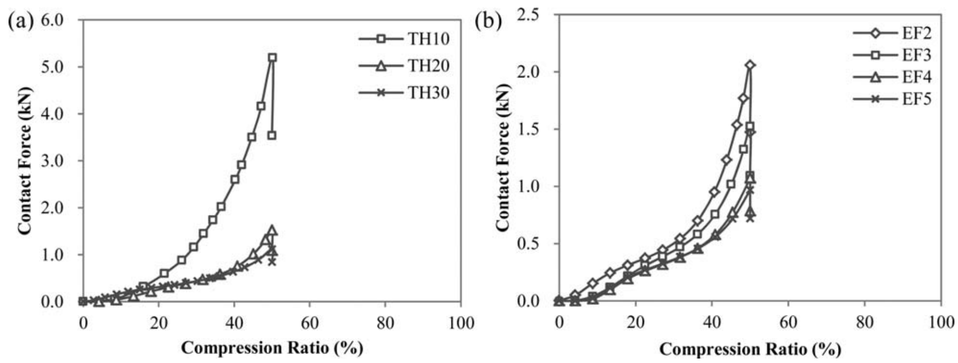

Figure 11. Compressive response to hardness of hybrid composites with various (a) panel thicknesses and (b) expansion factors.

Table II. Compressive Properties of Hybrid Composites

Sample	Hardness (N)	Drift rate (%)	IHF	IM	CFD-HL (%)	IFD-HL (%)
TH10	1476.28 ± 54.16	30.33 ± 1.63	301.93 ± 20.0	1.98 ± 0.20	—	51.57 ± 1.77
TH20	452.40 ± 27.39	28.52 ± 0.24	23.80 ± 8.6	0.85 ± 0.06	30.31 ± 1.55	33.56 ± 1.22
TH30	325.56 ± 33.16	24.40 ± 0.37	8.22 ± 1.57	0.60 ± 0.02	23.22 ± 1.47	37.59 ± 1.17
EF2	583.17 ± 36.40	28.67 ± 0.50	4.07 ± 0.78	1.09 ± 0.06	32.83 ± 0.49	38.07 ± 2.65
EF3	452.40 ± 48.66	28.52 ± 0.50	30.66 ± 8.76	0.80 ± 0.06	30.31 ± 1.55	36.79 ± 2.18
EF4	313.16 ± 24.97	26.96 ± 0.98	51.94 ± 1.50	0.75 ± 0.05	28.31 ± 0.78	32.34 ± 1.22
EF5	279.05 ± 21.50	26.21 ± 0.60	91.88 ± 9.18	0.75 ± 0.03	27.21 ± 1.28	30.95 ± 1.25

CHF-HL is the difference between loading energy and unloading energy by compressing 65% deflection. IFD-HL is the difference between loading energy and unloading energy by indenting 25% deflection. The reason for setting a different deflection with CFD-HL was that load of 65% IFD would exceed the rated capacity of 10 kN. 65% CFD of TH10 was unavailable because the value also exceeded the rated capacity of 10 kN.

all the samples successfully buffered more than 8.6 kN of the impact force. The cushioning force decreased with the improvement of expansion factor because decreasing cell wall collapsed to buffer the force. In terms of CLL, EP2 sample with the highest foam density presented the lowest loss ratio. In every impact, the CLL decreased with the expansion factor increasing from 3 to 5 because of reduced foam restriction to the hybrid laminates resulting less deformation. However, 20-mm thickness hybrid-laminated composites of various expansion factors exhibited CLL below 1.2 and presented good durability in cushioning capacity.

Compressive Properties

Hardness index is used to estimate the compressive loading bearing property of the hybrid laminated composites. Load drift exhibits after the peak load because of stress relaxation after the deflection maintaining for a period. Figure 11(a) illustrates the 50% compressive behavior of hybrid-laminated composites with different thicknesses. As the hybrid laminates had been processed by needle punching and thermal bonding, the internal structure was firm and compacted and the hybrid laminated composites have high stiffness. The contact force of hybrid-laminated composites was decreased with the promotion of

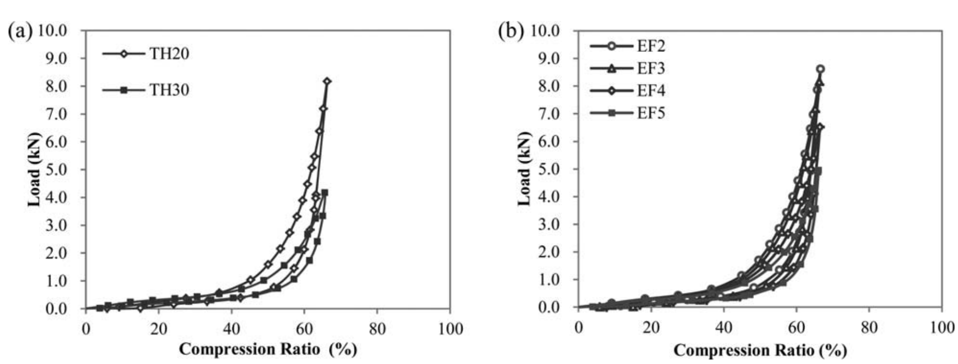

Figure 12. CFD hysteresis loss curves of hybrid composites with various (a) panel thicknesses and (b) expansion factors.

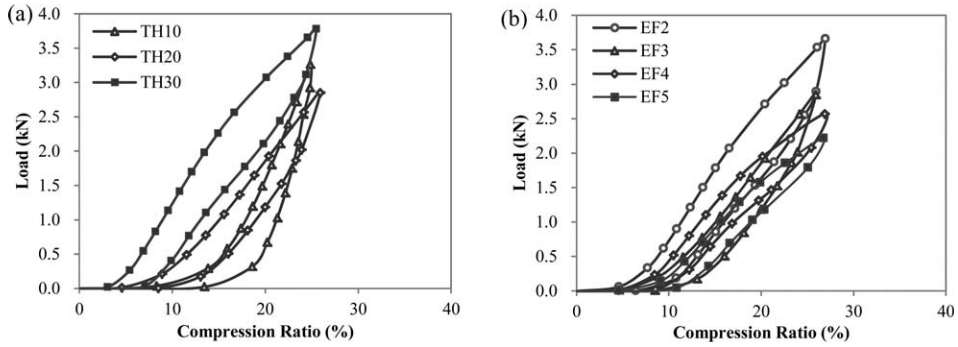

Figure 13. IFD hysteresis loss curves of hybrid composites with different (a) panel thicknesses and (b) expansion factors.

foam thickness. The main reason was that thicker composites provide more volume of foam to be deformed to disperse stress. It was apparent that TH 10 rose rapidly to 50% compression ratio, whereas other samples increased steadily. Drift rate (%) was in positive correlation with hardness value as listed in Table II. Effect of expansion factor on the hardness of hybrid-laminated composites was shown in Figure 11(b). Contact force was enhanced with the expansion factor decreasing and the foam density increasing. Hardness value also increased because the more cell wall collapsed to resist the compressive loading. Meanwhile, drift rate increased with the improvement of hardness and the decrease of expansion factor.

IHF and IM indicate the difficulty to compress the composites to 25 and 40% deflection, respectively. As seen from Table II, IM value varied with hardness value of the corresponding composites, which decreased with the increase in composite thickness and expansion factor. In terms of IHF, the value also decreased with composite thickness increasing and, however, with expansion factor decreasing. The reason was that hybrid composites with compacted structure enhanced the indentation threshold, and the difference between 5% IFD and 25% IFD value in higher expansion factor was much greater than the difference value in lower expansion factor samples.

Hysteresis phenomenon is generated by energy absorption under compressive loading exhibits in all composites. The value of hysteresis loss indicates the cushioning capacity and resilience property of the hybrid-laminated composites. Based on the compression position, the hysteresis mechanism of CFD is collapse of foam cell and failure of thermal-bonding point, whereas the mechanism of IFD additionally includes tensile fracture of the hybrid laminates. Figure 12 illustrates the compressive behavior of 65% compression of the composites samples. It is clear that samples of all the constructions recovered to almost the original thickness which indicated that the samples had good recovery properties after compressive deflection. The maximum compression force increased with the decrease in composite thickness [Figure 12(a)]. This peak load at 65% compression of TH30 was nearly half of TH20 because the more load on TH30 was dissipated through deformation of more volume of foam in vertical structure. Figure 12(b) shows that the peak load of the hybrid-laminated composites decreased with the increase of expansion factor. On the other hand, the hysteresis loss of CFD value of hybrid-laminated composites decreased with the increase of expansion factor which meant that foam with lower density had better recoverability (Table II).

Every hybrid-laminated composites sample presents an IFD-HL higher than 30%. The main reason was that the reinforcing fibers were restricted by foam and were broken by tearing and tensile force to resist the load. As main failure mechanisms, fracture of fibers and thermal bonding points under the indentation load are irreversible damage. The higher foam density led more restriction to the reinforcing fibers and caused more fiber fracture and laminates deformation. Laminates in EF2 were restricted with the highest foam density and were deformed under quasi-static compression loading. Thus, as seen in Figure 13(b), the contact force under unloading dropped markedly and the highest IFD-HL value was proposed.

CONCLUSION

In this study, intra/interply hybrid laminates reinforced high-density flexible foam composites were successfully prepared. The effects of materials parameter, including composite thickness and expansion factor, on the tensile and compressive properties of the hybrid-laminated composites were investigated. The results revealed that hybrid laminates strengthen the sandwich hybrid composites, and tensile strength and modulus were significantly enhanced. Tearing resistance in parallel and perpendicular directions were both improved with expansion factor increasing and, however, exhibited opposite tendencies with the increasing composite thickness because bending strength played an important role in tearing behavior. Tearing resistance in perpendicular direction was higher than in parallel direction because of the reinforcement of hybrid laminates. As laminates were restricted by foam adhesion, the delamination resistance to surface layer and second layer both in crease with foam density. Most samples could buffer more than 95% incident force in the dynamic cushioning impact and TH30 buffered up to approximately 98.5%. Composite thickness and expansion factor significantly influenced the hardness, IHF, and IM. The intra/interply hybrid-laminated composites presented hysteresis loss ranging from approximately 30 to 38% because the damage of hybrid laminates was unrecoverable.

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