Composites Part B 83 (2015) 253–263

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Quasi-static and dynamic mechanical responses of hybrid laminated composites based on high-density flexible polyurethane foam

Ruosi Yan [a], Rui Wang [a], Ching-Wen Lou [b], Shih-Yu Huang [c], Jia-Horng Lin [c], [d], [e], *

[a] *School of Textiles, Tianjin Polytechnic University, Tianjin 300387, China*
[b] *Institute of Biomedical Engineering and Materials Science, Central Taiwan University of Science and Technology, Taichung 40601, Taiwan*
[c] *Laboratory of Fiber Application and Manufacturing, Department of Fiber and Composite Materials, Feng Chia University, Taichung 40724, Taiwan*
[d] *School of Chinese Medicine, China Medical University, Taichung 40402, Taiwan*
[e] *Department of Fashion Design, Asia University, Taichung 41354, Taiwan*

ARTICLE INFO

Article history:
Received 26 December 2014
Received in revised form
16 April 2015
Accepted 7 August 2015
Available online 20 August 2015

Keywords:
A. Hybrid
A. Foams
B. Mechanical properties
D. Mechanical testing

ABSTRACT

Hybrid laminated composites were fabricated based on high-density flexible polyurethane foam and reinforced with inter/intra-ply hybrid laminates. Transient responses of hybrid composites under quasi-static and dynamic loadings with various thicknesses and expansion factors were comparatively investigated. Experimental results revealed that foam cell collapse and hybrid laminates rupture were dominant mechanisms of energy absorption. Interlaminar stress and composite tensile strength determined the compressive potential energy and double-peak behavior. Quasi-static bursting and puncture resistances exhibited totally different relationships to various constructions and expansion factors. Energy dissipation capacity is influenced more significantly by the constant rate of transverse (CRT) puncture than dynamic puncture process. CRT puncture resistance is superior to the corresponding dynamic puncture resistance for all constructions. The hybrid laminated composites contributes to eliminate more than 95% of the incident force in the drop weight impact test. Compared with non-laminated panel, the hybrid laminated composites exhibited higher resistance to static and dynamic loadings.

1. Introduction

Quasi-static loading is a common damage mode of hybrid laminated composites during application in packaging, interior wall of a soundproofing room, and containers; for example, long-term indenting or squeezing occurs when the material comes in contact with the protected objects. Dynamic impact damage occurs when the composite panel is attacked by foreign sharp or blunt objects. Comparing the five hybrid composite classifications, namely, inter-ply, intra-ply, intimately mixed, selective placement, and super-hybrid composites [1–3], inter-ply and intra-ply hybrid structures were considered suitable for reinforcing the energy management (energy absorption and dissipation) of the materials. Investigations proposed by Lin et al. [4,5] demonstrated that inter-ply and intra-ply hybrid laminates with various stacking sequences exhibited high resistance to static and dynamic punctures. Previous studies reported the effects of rigid surface reinforcement on flexible foam based composites, such as metallic panels. However, rigid surface reinforcement may eliminate the advantages of flexible substrate, such as high cushioning ability, and cause damage, such as secondary collision. Therefore, textile based hybrid laminates are suitable for applying as surface reinforcement incorporated into high-density flexible foam. Flexible textile fabric based on high-performance fibers, such as aramid, basalt, ultra-high-molecular-weight polyethylene, glass, and carbon fibers, with diverse structures are commonly used to reinforce the strength and modulus of composites [6–8]. Hosur et al. [9] explored quasi-static and dynamic puncture behavior of impregnated aramid woven fabric hybrid laminated composites. Koerner et al. [10] investigated the manufacturing and puncture resistance of intra-ply hybrid nonwoven fabric. Ahmad et al. [11] found that unidirectional coated fabric performed quasi-static puncture resistance. Baucom et al. [12] analyzed failure mechanisms of 2D and 3D woven composites under quasi-static perforation. Woven, nonwoven, unidirectional,

---

* Corresponding author. Laboratory of Fiber Application and Manufacturing, Department of Fiber and Composite Materials, Feng Chia University, Taichung 40724, Taiwan, ROC.

E-mail addresses: jhlin@fcuoa.fcu.edu.tw, jhlin@fcu.edu.tw (J.-H. Lin).

http://dx.doi.org/10.1016/j.compositesb.2015.08.037
1359-8368/

and integrated 3D structures are considered to spread transverse and longitudinal waves to dissipate incident energy in different degrees.

Flexible polyurethane foam is extensively used in various applications, including civil engineering, automotive, packaging, and personal protection, because of its excellent performance in thermal insulation, acoustic absorption, and energy management, as well as light weight. Chemical composition, degree of crystallinity, and cross-linking contribute to chemical resistance and cushioning properties of polymeric foam which, however, are weak in tensile and tear performances [13]. Incorporating with reinforcements can overcome the drawbacks of the mechanical properties of foam. Researchers have attempted to reinforce the impact resistance of rigid foam by adding fillers [14], laminating [15,16] stitching [17], and diverse methods [6,18,19]. Flexible foam provides high compression potential energy, high resilience, and excellent energy absorption through deformation [20–22], but has inferior cut and puncture resistance, which results in its poor energy dissipation ability under localized loading. Malekzadeh et al. investigated [23,24] the low-velocity impact response of composite sandwich panels with transversely flexible core. Zaretsky et al. [25] studied the in-plane impact response of high density flexible polyurethane foam. Many studies focused on low-density (20 kg/m^3 to 100 kg/m^3) high-resilience foam, whereas few studies examined high-density (200 kg/m^3 to 3000 kg/m^3) high-resilience flexible foam. Studies on localized loading were very rare.

The effects of textile laminate-reinforced foam composites on quasi-static and dynamic loading responses are examined in the present study. The study focused on manufacturing high-density flexible polyurethane foam based hybrid laminated composites and experimentally investigating their responses under quasi-static and dynamic loadings. Reinforced with recycled Kevlar/glass inter/intra-ply hybrid laminates, composite panels with transverse foam cores were fabricated with different thicknesses of 10, 20, and 30 mm and expansion factors ranging from 2 to 5 to evaluate their influence on mechanical properties. For comparison, a foam panel without laminated reinforcement was also fabricated. The failure mechanisms CRT puncture, drop-weight puncture, static bursting and dynamic cushioning characteristics were observed and analyzed.

2. Experimental procedure

2.1. Materials and composites fabrication

The sandwich structure hybrid laminate sheet used to reinforce the composites was a combination of double-recycled Kevlar nonwoven layers with a glass plain fabric center layer manufactured via needle punching and thermal bonding. Hybrid nonwoven fabric was composed of Kevlar staple fibers with a length of 50 mm to 60 mm that were collected from recycled selvages of unidirectional fabric (DuPont Company, USA), which are used to strengthen the rupture resistance of laminates, and 4 denier sheath–core bicomponent polyester staple fiber (low-melting point polyester [LMPET], purchased from Far Eastern Textile Ltd., Taiwan), which has a low melting point of 170 °C, and integrated through needle punching. Then, double Kevlar/LMPET nonwoven layers with E-glass plain woven fabric (Jinsor-Tech Industrial Corp., Taiwan) center ply were laid up and incorporated into the sandwich structure by needle punching at 100 strokes/min. Thermal treating at 180 °C for 15 min could generate thermal bonding points based on LMPET to strengthen the nonwoven web and interlaminar stress between nonwoven and glass fabric. The microphotograph of the intra-ply hybrid nonwoven fabric is shown in Fig. 1(a). The basic mechanical properties of the resultant hybrid laminates which have been studied in our previous work [26–28] are tabulated in Table 1.

The high-density flexible polyurethane foam based composite panel was prepared with three different thicknesses (TH) of 10, 20, and 30 mm and four foam expansion factors (EF) of 2, 3, 4, and 5. High resilience was obtained by reducing the dominant intermolecular interactions, including hydrogen bonding of urethane linkages and irregular structures of polymeric molecules [29]. APEXLON® UR-248 polyether polyol was mixed with a combination of toluene diisocyanate and polymeric methylene diphenyl diisocyanate (TDI/MDI at a weight ratio of 80/20) (KLS Corporation, Taiwan) at a weight ratio of 4:1 and agitated at a speed of 1200 rpm for 15 s for complete cross-linking reactions. The gel mixture was infused into aluminum molds of 300 × 300 × [10, 20, or 30] mm^3 dimensions with reinforcing hybrid laminates laid at the top and bottom. Then, the molds were closed for expanding and curing. Expansion factor, which was determined through reaction time and pressure, was a dimensionless parameter calculated as follows:

$$\mathrm{EF} = \frac{V_\mathrm{r}}{V_\mathrm{i}} \tag{1}$$

where V_i is the volume of the mixture (m^3) and V_r is the volume of the foam (m^3). The cell structure of pure high density flexible foam is shown in Fig. 1(b). The infused mixture reacted and expanded rapidly through gas generation. Foaming pressure was high in the closed mold such that the polymer infiltrated the nonwoven layers and saturated the voids. The microphotograph of cured hybrid composites is shown in Fig. 1(c)–(e). After curing at 25 °C for 2 h, the sandwich hybrid composite panel was demolded. The construction of the resultant sandwich hybrid composites was shown in Fig. 2. For comparison, non-laminated (N-L) composite panel, which was reinforced with normal polyester nonwoven fabrics instead of hybrid laminates, was also fabricated. The specifications of hybrid composites which have been investigated in our previous work [30,31] are presented in Table 2.

2.2. Testing

Transient responses of flexible foam based hybrid laminated composites were tested under quasi-static and dynamic loadings. Quasi-static bursting test was conducted on an Instron 5566 universal testing machine (UTM) according to ASTM D3787. Specimens were trimmed to dimensions of 125 × 125 mm^2 and clamped between fixtures with 45 ± 0.005 mm-diameter apertures at the centers. The 7 ± 0.05 mm-diameter hemispherical-end probe punched the specimen at a crosshead speed of 100 mm/min until the panel was penetrated (Fig. 3(a).). Data was analyzed in terms of load and fracture work.

Puncture resistance was evaluated by Instron 5566 UTM based on ASTM F1342. The crosshead probe had a conical head with a diameter of 4 mm. Specimens were trimmed to dimensions of 100 × 100 mm^2 and punctured at a constant velocity of 508 mm/min. The CRT puncture test equipment is schematically shown in Fig. 3(b).

Drop-tower device (Kuang-Neng Machine Factory Co. Ltd., Taiwan) was applied to carry out the dynamic puncture tests according to NIJ Standard 0115.00. The device was equipped with a PCD330A impulse data acquisition system to record data at 2000 Hz. A specimen with a dimension of 100 × 100 mm^2 was held by the fixture with 40 mm-diameter apertures. A 4 mm-diameter probe on the cross-head load cell weighing 8.26 kg was released freely from a height of 284 mm to the composites surface, guided by two smooth columns. The instrument is shown in Fig. 3(c).