Carbohydrate Polymers 91 (2013) 659–665

Contents lists available at SciVerse ScienceDirect

Carbohydrate Polymers

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

Review

Beetle forewings: Epitome of the optimal design for lightweight composite materials

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ARTICLE INFO

Article history:
Received 29 June 2012
Received in revised form 26 July 2012
Accepted 17 August 2012
Available online 28 August 2012

Keywords:
Biomimetic composite material
Beetle forewing
Allomyrina dichotoma
Prosopocoilus inclinatus
Design optimization

ABSTRACT

Based on studies of the forewings of two beetles, *Allomyrina dichotoma* and *Prosopocoilus inclinatus*, this paper reviews and identifies the potential benefits of studying the structure of the beetle forewing and the associated development of lightweight biomimetic composite materials. The forewings of both beetle species consist of an integrated border frame structure and a large center part with distributed trabecular supports in the hollow core. The forewings of the male *A. dichotoma* are constructed to reflect a lightweight honeycomb design. However, the forewings of *P. inclinatus* are a durable structure. The biological significance of these structures is also discussed. This work proposes an integrated honeycomb structure inspired by the beetle forewing. A series of biological models are also proposed for lightweight integrated honeycomb structures and durable sandwich structures with a trabecular core, which are intended to establish a new direction in the development of biomimetic composite materials.

Contents

1. Introduction

Optimization algorithms are often employed as the primary approach to design optimization problems. In fact, living organisms in nature already possess highly optimized structures, which have been established by a long history of survival and adaptation to the natural environment. This notion forms the basic underlying principle for the field of biomimetic optimization techniques (Burte, Deusen, Hemenger, & Hedberg, 1986; Thompson, 1961). Insects were one of the first phylogenetic groups of animals to appear on Earth and have evolved over an extremely long period of time. More than 600,000 different species of insects are in existence today (Nakane, Oobayashi, Nomura, & Morimoto, 1978), and modern insects provide biomimetic researchers with numerous highly refined design inspirations (Gullan & Cranstion, 1994; Hepburn, 1976).

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http://dx.doi.org/10.1016/j.carbpol.2012.08.061

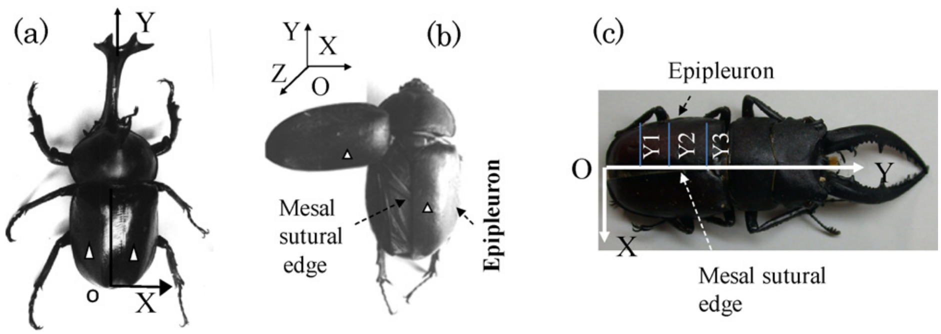

Fig. 1. Beetles: representative male (a) and female (b) specimens of *A. dichotoma* and (c) male *P. inclinatus*. Δ: forewing regions; Y1–Y3, the observational positions for analysis.

Until recently, the beetle forewing was mistakenly classified as non-living matter (Ishii, 1982), and perhaps for this reason, its structure has historically drawn little attention from biologists and biomimetic engineers. In the literature, most studies have focused on several specific aspects of the beetle forewing, which include the appearance and composition of the structure (Barbakadze, Enders, Gorb, & Arzt, 2006; Gullan & Cranstion, 1994; Youdeowei, 1977), the arrangement of the chitin fiber (Chen, Iwamoto, Ni, Kurashiki, & Saito, 2000; Chen, Peng, & Fan, 2000; Zelazny & Neville, 1972), and the mechanical properties of biomimetic composite materials (Gokan, 1966; Wainwright, Biggs, Currey, & Gosline, 1982). Since 1997, the author has undertaken a systematic line of investigation on the cross-sectional microstructure of the beetle forewing (Chen, Iwamoto, et al., 2000; Chen & Ni, 2003); this work has revealed the laminated structure (Chen, Iwamoto, Ni, Kurashiki, & Saito, 2001a; Chen, Dai, Xu, & Iwamoto, 2007) and the internal fine structure (trabecular framework) of the forewings of beetle species such as *Allomyrina dichotoma* (Chen, Iwamoto, Ni, Kurashiki, & Saito, 1999; Chen, Ni, Endo, & Iwamoto, 2001; Chen, Ni, Endo, & Iwamoto, 2002). Preliminary investigations have demonstrated that the beetle forewing possesses excellent mechanical properties (Chen, Iwamoto, Ni, Kurashiki, & Saito, 2001b), and a corresponding structural model has been proposed. Chen, Peng, and Fan (2003) reported on the mechanical properties of the forewing structure and the strength of a biomimetic composite material consisting of small holes. Dai and Lomakin et al. conducted in-depth analyses of the mechanical properties, such as the surface hardness of the forewing and the connective forces and the clavus-locking structure of the left and right forewings (Yang, Wang, Yu, & Dai, 2007; Dai & Yang, 2010; Frantsevich, Dai, Wang, & Zhang, 2005; Lomakin et al., 2010, 2011). Kamp (Van De Kamp & Greven, 2010) and Lenau et al. (Lenau & Barfoed, 2008) studied the arrangement of beetle forewing fibers, and Guo et al. (Guo & Wang, 2011) confirmed and reported that the trabecular structure is an excellent energy-absorbing structure for biomimetic applications. Beetles come in an extensive variety of types and sizes, and even within the same species, the horns of female beetles are typically smaller than those of the males; additionally, beetle species tend to exhibit significant differences in their body shapes according to sex. Therefore, this paper summarizes work that has been conducted by the author on the forewing structure of *Prosopocoilus inclinatus* and *A. dichotoma* (Chen, Iwamoto, Ni, & Kurashiki, 2002; Chen, Guo, et al., 2012), including relevant key developments in research on lightweight biomimetic composite materials (Chen, Ni, & Xie, 2012; Chen, Wu, Wu, Xie, & Zhu, 2012; Chen, Xie, et al., 2012). Furthermore, the design optimization techniques and their respective significance for biological structures are discussed in a manner that definitively presents the elegant style of the beetle forewing as a lightweight, high-strength optimization design model.

2. The optimal structure and biological significance of the beetle forewing

The beetles used in this experiment are adult male and female *A. dichotoma* and male *P. inclinatus* (Fig. 1). The observational positions of each specimen are shown in Fig. 1(c), which presents an approximate division of the beetle into three regions: the front, the middle, and the back, represented as Y1, Y2, and Y3, respectively.

The structural optimization and the biological significance of the forewing structures will be described comprehensively based on the spatial relationships of the key forewing locations, from the vertical cross-section *X*–*Z* to the fiber lamination in the horizontal plane *X*–*Y*, in addition to the internal trabecular structure. Due to space limitations, the horizontal fiber laminated structure (the plane *X*–*Z*) will not be discussed in detail.

2.1. The structure of the beetle forewing

2.1.1. Cross-section and frame structure of the beetle forewing

Fig. 2(a) and (b) shows the cross-sections of the right wings of two beetles (in the *X*–*Z* plane), Fig. 3(a) and (b) shows a magnified image of a trabecula in cross-section, and Fig. 3(c) shows a simplified model depicting all of the characteristic parameters of the cross-section (Chen, Iwamoto, et al., 2000). Figs. 2 and 3 show that the forewing structures of both beetles are formed by an upper lamination, a lower lamination, and a central void, which consists of trabeculae. Furthermore, large void regions exist in the frame structure at its left and right ends, as shown in the image. These large voids can be approximated as either a hollow rectangle or a hollow

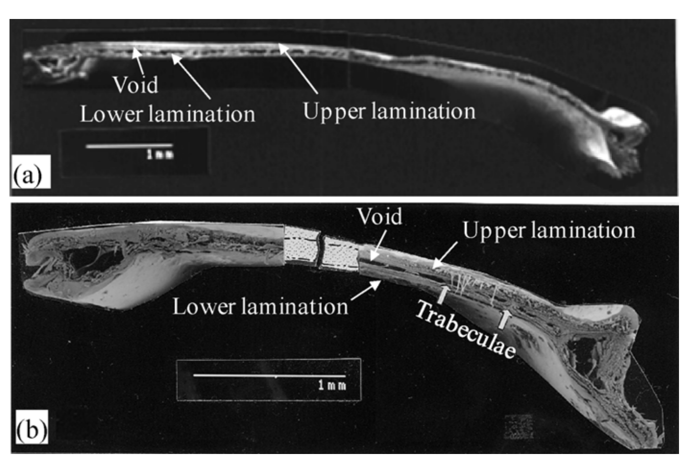

Fig. 2. Frame structure in the cross-section of the beetle forewing: (a) *A. dichotoma* at section position Y2 and (b) *P. inclinatus* at section position Y3.

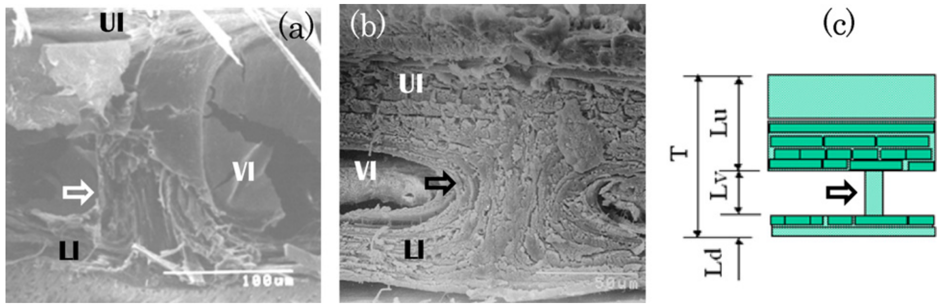

Fig. 3. Trabecular characteristics of *A. dichotoma* (a) and *P. inclinatus* (b). (c) A simple trabecular model. Ul: upper lamination; Vl: void lamination; Ll: lower lamination; ⇨ : trabecula.

triangle in cross-section, and at locations closer to the root structure of the forewing, the aspect ratios of these void structures increase. It has been previously demonstrated for structural designs with variable cross-sections that the moment of inertia of the horizontal axis increases for example closer to the forewing root. Overall, this design satisfies the bending stiffness and torsional rigidity (Chen, Iwamoto, et al., 2000) requirements of forewing function. While the total thickness *T* of the forewing cross-section remains approximately the same along the length of the central void and frame structures of both beetles, the central void of *A. dichotoma* is larger than that of *P. inclinatus*; conversely, the sum of the thicknesses of both the upper and lower laminations (Lu + Ld) is smaller in *A. dichotoma* than in *P. inclinatus*.

Additionally, with respect to the central region in particular, the laminated structure of the forewing fiber of a male *A. dichotoma* typically consists of approximately 10 layers, with a non-equiangular structure residing between two adjacent lamination layers. However, more than 20 such layers are found in *P. inclinatus*, and they all tend to be equiangular (72°) between the adjacent layers.

2.1.2. Trabecular structure and distribution characteristics within the beetle forewings

Fig. 3 shows that the trabecula of *A. dichotoma* is thin and long, whereas that of *P. inclinatus* is thick and short. Internally, the fibers of the trabeculae are interconnected with the fibers of both the lower and upper laminations at obtuse angles and form a single living entity (Chen, Ni, et al., 2001; Chen, Ni, et al., 2012). The upper lamination is thicker than the lower lamination in *A. dichotoma*; yet, in *P. inclinatus*, the distance between the upper and lower lamination is smaller.

Fig. 4(a) and (b) presents images of the forewings of both beetle species following a 3-hour boiling treatment in 10% KOH solution. Numerous small black dots can be observed on the wing, where each dot represents a single trabecula (Chen, Ni, et al., 2002; Chen, Ni, et al., 2012). The trabecular density was calculated using the average density values of nine squares, each measuring 1 mm^2, as shown in Fig. 4. The average trabecular density of the forewing of *P. inclinatus* was determined to be 35 (number of trabeculae per square of mm), whereas for *A. dichotoma*, the density was calculated to be 6, representing a 6-fold difference in the trabecular densities. Fig. 4(c) and (d) shows images of pristine forewings of both *A. dichotoma* and *P. inclinatus*. The images show that both beetles possess numerous trabeculae. It has been previously demonstrated that the use of a trabecular structure in laminated composite materials can effectively improve their anti-stripping performance (Chen et al., 2001b). Additionally, the forewing of *A. dichotoma* consists of an extensive honeycombed structure formed of honeycomb-structured air sacs; however, no such structures can be observed in *P. inclinatus*.

2.1.3. Strength and appearance characteristics of male and female A. dichotoma forewings

The weights and dimensions of live male and female *A. dichotoma* beetles and their forewings were measured (Chen et al., 2007). The differences in the measurements according to sex were significant, with $P\,(t_0) \leq 0.05$. The results indicate that male

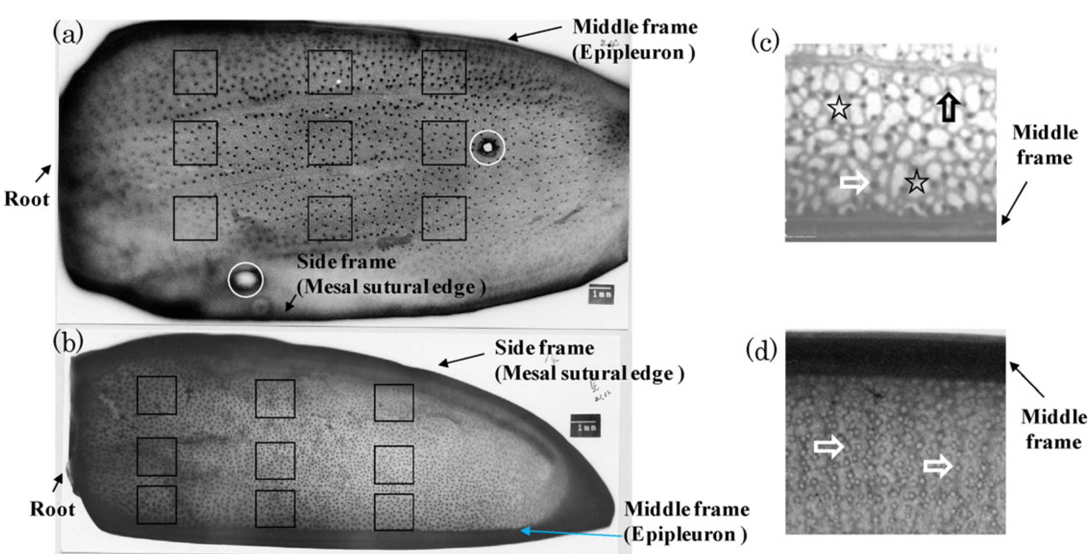

Fig. 4. The forewing and its trabecular distribution after the 10% KOH treatment (a and b), and the pristine forewings (c and d). (a and c) *A. dichotoma*, (b and d) *P. inclinatus*. ◯: holes are due to damage incurred from beetle battling behavior, ⇨ : trabecula, ☆: air sacs.

Table 1
Tensile results of the forewing.

Beetle	Male *A. dichotoma*		Female *A. dichotoma*		*T*-test
Object	Average	STDEV	Average	STDEV	*P*
Force (kN)	28.1	5.9	35.6	2.3	0.00*
Thickness (μm)	54.0	7.2	69.7	8.0	0.00*
Stress (MPa)	130.7	25.8	127.9	25.2	0.49

* Indicate a significant difference at normal significance level $P \leq 0.05$.

beetles are larger and heavier than females, with a weight difference of approximately 18%. The forewing dimensions were also larger (+13%) in the male beetles, but there was no significant difference between the forewing weights. In fact, the weight of the male forewing was slightly less than that of the female (−5.6%).

Table 1 presents the average tensile break stresses of the forewings of both *A. dichotoma* males and females under different loading directions, and they were calculated using the breaking force and the thicknesses of the upper and lower laminations. Table 1 shows that the breaking force of the forewing was significantly different between the males and females. The breaking force of the male forewing was 20% lower than that of the female forewing; however, the tensile break stress was not significantly different.

2.2. Optimal structure of the beetle forewing and its biological significance

2.2.1. Optimal structure of the forewing by sex and its biological significance

As mentioned earlier, while the weight of the male *A. dichotoma* beetle exceeds that of the female (+18%), the weight of the male forewing is slightly less (to an insignificant degree) than that of the female. To sustain flight, the dimensions of the male forewing must be significantly larger. Using the simple dimensional measurements (Chen et al., 2007), the average area of the male forewing was calculated to be approximately 13% larger than that of the female forewing, which leads to a reduction in the difference between the male and female forewings in terms of the load per unit area, which is only 7.1% higher in the male than in the female. However, the male forewing should possess a greater ability to bear its own weight. The male *A. dichotoma* also possesses a prominent horn structure (Fig. 1a), which is used either for attacking others or in self-defense. The required use of the forewing for self-defense behavior is significantly reduced by the presence of a horn, which allows for the construction of the forewing to be thinner and thus lighter in weight. In support of this argument, the data in Table 1 demonstrate that the thickness of the male forewing is smaller than that of the female by 23%. However, reproduction is the primary responsibility of the female, and because females lack horns, their only method of self-defense includes avoiding direct confrontation or relying on the forewing for protection. The similarities in the compositions of the chitin fibers of the male and female forewings are likely the source of the similarity in the tensile break stresses (Table 1). However, the breaking force and thickness measurements of the female beetle forewing are greater than those of the male by more than 25%. The biological significance of this sex-related difference can be explained by the respective living habits of the beetle sexes. *A. dichotoma* males tend to be aggressive and constantly competing for food and mating partners, so they regularly engage their horns (Fig. 1a) to pierce the forewings of their competitors, which leaves behind puncture wounds (Fig. 4a). Of the first 20 deaths in a captive breeding population of beetles (Chen et al., 2007), 70% were male, with an average of 2.4 puncture wounds per beetle; however, an average of only 0.2 holes was calculated for the female beetles, representing a 10-fold difference by sex, despite the difference in the proportions of male and female *A. dichotoma* beetles involved in battling behaviors. Moreover, the purpose of this study did not extend to investigating the relationship between damage to the beetle forewing and its lifespan. The following conclusion can be inferred based on these results: to increase its self-defense capabilities and extend its lifespan and reproductive cycles to ensure the production of offspring, the thickness of the forewing has been increased in the female *A. dichotoma* compared to the forewing of the male beetle, which allows it to achieve increased mechanical strength.

2.2.2. Structural optimization and the biological significance of different beetle forewings

While the forewings of both beetle species are constructed to yield a lightweight structure with a central void and a variable cross-section frame, significant differences are still present. For example, compared to *A. dichotoma*, the trabeculae within the forewing of *P. inclinatus* are shorter and thicker (Fig. 3), and the density of the trabeculae in *P. inclinatus* is also six times greater than that of *A. dichotoma* (Fig. 4). *P. inclinatus* has a smaller central void area (in cross-section), and the sum of the thicknesses of its upper and lower lamination layers is twice that of *A. dichotoma* (Fig. 3) (Chen, Iwamoto, et al., 2000). Therefore, it can be concluded that the forewing of *P. inclinatus* is more durable in terms of structural design, whereas the forewing of *A. dichotoma* is a more lightweight structure. The former (*P. inclinatus*) is the result of an extensive number of structural changes that together achieve a lightweight and high-strength design; such changes include the diameter of the trabeculae, the trabecular density, the thicknesses of the upper and lower laminations, the angle between adjacent laminations, and the number of interlayer equiangular laminated layers. The latter (*A. dichotoma*) is the result of a different optimized design, which includes cone-shaped trabeculae, a honeycomb structure, and non-equiangular fibers in the lamination layer (male); combined, these forewing structures yield a lightweight composite. The following question remains: why are there such differences between the two types of beetles? The author believes that the differences are related to the lifespans of the two beetle species (Ueno, Kurosawa, & Sato, 1999). To rationalize this hypothesis, a crude estimate of the lifespan of *P. inclinatus* of 2 years and that of *A. dichotoma* of just 1–2 months is utilized, which is a 10-fold difference by species. From an engineering perspective, we might consider *P. inclinatus* to be a “durable good,” whereas *A. dichotoma* is only a “one-time consumable.” Therefore, in terms of design methods, *P. inclinatus* strengthens its wings by an increase in quantity, while *A. dichotoma* may rely solely on its ingenious and unique structural designs (Chen et al., 2007). Additionally, beyond the aforementioned honeycomb and non-equiangular laminated structures, the lower lamination of the forewing of *A. dichotoma* is exceptionally thin, measuring approximately just one-third that of *P. inclinatus*. This reduction in thickness is likely accommodated by the fact that the lower lamination is closest to the body, which reduces its probability of sustaining damage during external attacks; thus, the thickness of the lower lamination is reduced to eliminate the use of unnecessary material. At the same time, the holes observed on the forewings of male *A. dichotoma* beetles are the result of battling behaviors, which suggests that the “one-time consumable” design was selected at a considerable cost to the strength of the forewing.

Therefore, the biological structures of different beetles are each specialized for specific functions, for particular living habits, and for overall adaptation to their environments; additionally, these structures also provide natural inspiration for the design of high-strength and lightweight composite materials. Taking the integrated lightweight, high-strength honeycomb structure of *A. dichotoma* as an example, its structural characteristics and formation mechanism will be further described below. The latest progress

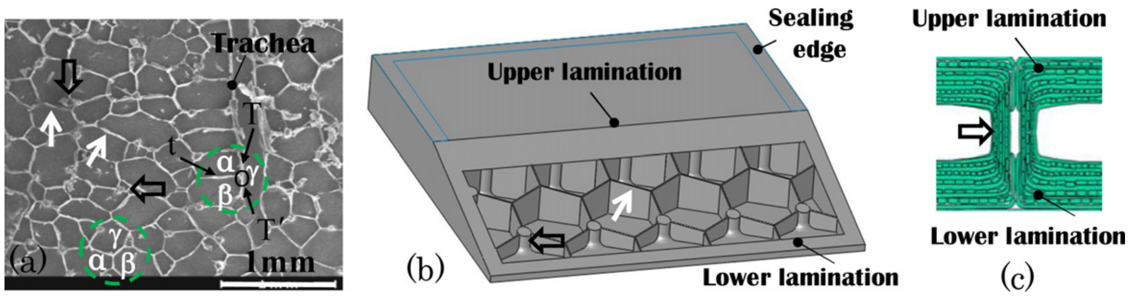

Fig. 5. The trabecula–honeycomb structure of the forewing of *A. dichotoma*, and a schematic of the biomimetic edge sealing technique. (a) The microstructure of the forewing. (b) An oblique cross-section. (c) Schematic view of the trabecula with reinforcing fibers. ⇨ : a trabecula, →: the honeycomb wall.

in the development of biomimetic composite materials will also be described.

3. The integrated honeycomb structure and the development of a biomimetic composite

3.1. Design of a lightweight, high-strength model: the integrated honeycomb structure

Fig. 5(a) shows the microstructure of the forewing of *A. dichotoma* following the removal of its lower lamination. By combining Fig. 2, Fig. 3, and Fig. 4(c), a schematic structure was generated that illustrates the complete integrated trabecula–honeycomb model (Fig. 5b) (Chen, Xie, et al., 2012; Chen, Ni, et al., 2012). In other words, we have developed an edge-sealing technique inspired by the beetle forewing for use in an integrated honeycomb biomimetic material. The fibers within each trabecula reinforce the structure by alignment in either a unidirectional or spiral fashion with the fibers of the upper and lower lamination layers, as shown in Fig. 5(c). The formation mechanism used to construct the integrated trabecula–honeycomb panel structure and its resulting mechanical characteristics are described below.

Thompson's cell partition theory (Thompson, 1961) states that, as shown in Fig. 5(a), the angles (α, β, and γ) between in vivo cell walls at the intersection point O depend on the relationship between the three tensions T, T', and t: (a) when $T' = T \gg t$, i.e., when t is negligible compared to T' and T, then α and β are right angles; and (b) when $T' = T = t$, then α, β, and γ are equiangular at 120°. Let us consider the reticular distribution pattern of the forewing of *A. dichotoma*. The trachea are more robust than the walls of the air sac, and we find that the equation reduces to $T' = T \gg t$, resulting in a 90° angle between the air sac and trachea, as shown on the right side of Fig. 5(a). However, the vast majority of the air sac cells present in the interior of the forewing are in equal-tension states (Fig. 5a), leading to the formation of a honeycomb structure with 120° angles between the air sac walls, as shown in the lower left corner of Fig. 5(a). The presence of the trabeculae and the border structures gives the forewing sufficient flexural and compressive strength and effectively increases the peel strength between the upper and lower laminations of the forewing. Furthermore, with the characteristic overlay angles between the fiber layers of the upper lamination and the variable cross-section design of the frame, the overall structure of the forewing confers the mechanical properties required for flight. Thus, the forewing of *A. dichotoma* has evolved as a complete integrated trabecula–honeycomb structure (Chen, Xie, et al., 2012).

However, it is well known that some biological structures exhibit extreme complexity in design. As shown in Fig. 5(b), there are voids inside the honeycomb plate (Gibson, Ashby, & Harley, 2010). The forewing consists of several hundreds (or perhaps even thousands) of trabeculae serving as connections between the upper and lower lamination layers. Within the trabecula–honeycomb plate, the fibers are distributed continuously. The difficulties of manufacturing such structures by molding are obvious. We have been searching for approaches to manufacture such delicate biological structures since 2000 and have only succeeded recently (Chen, Guo, et al., 2012).

3.2. Development of the integrated honeycomb-columnar structure

Fig. 6 presents a schematic of a series of simple mold devices. Fig. 6(a) and (b) shows a female mold and a basic male mold, respectively. Fig. 6(c) shows a combined assembly of both the male and female mold components, and Fig. 6(d) shows a schematic of the expected product. To fabricate the trabecula–honeycomb structure, the male molds (composed of paraffin) were first fit onto the female mold, which was lined with a basalt fiber mesh. Then, chopped basalt fibers and epoxy resin were added to the mold. The overall assembly was cured at a low temperature and then heated to melt away the paraffin male mold, thereby forming the integrated trabecula–honeycomb panel (Chen, Guo, et al., 2012; Chen, Xie, et al., 2012). Fig. 6(e) shows a hand-made sample of the trabecula–honeycomb product. The honeycomb and trabecular structures and the pattern are clearly shown in Fig. 6(e);

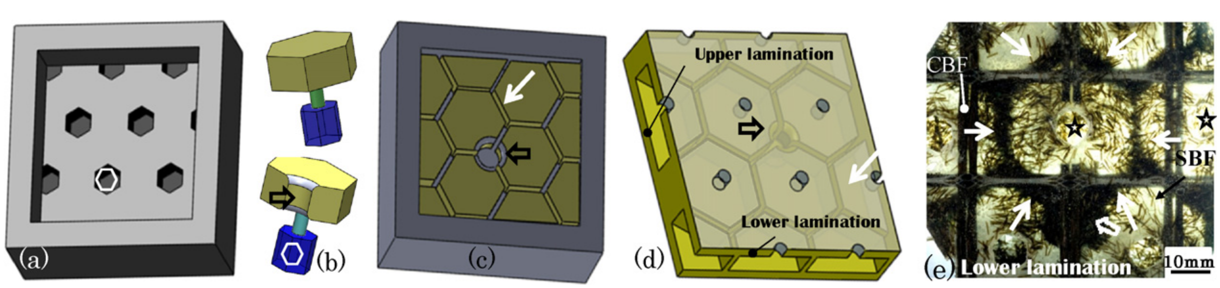

Fig. 6. Molding tools developed for the integrated manufacturing of trabecula–honeycomb plates: (a) a female tool, (b) basic male tools, (c) assembly of the tools, (d) a schematic of the expected product, and (e) the bottom view of an example. ⇨ : a trabecula or the space used to form a trabecula, →: a honeycomb wall or the space used to form a honeycomb wall, ⬡ : either a positioning hole or a positioning block, ☆: a processing hole; SBF denotes the short basalt fiber.

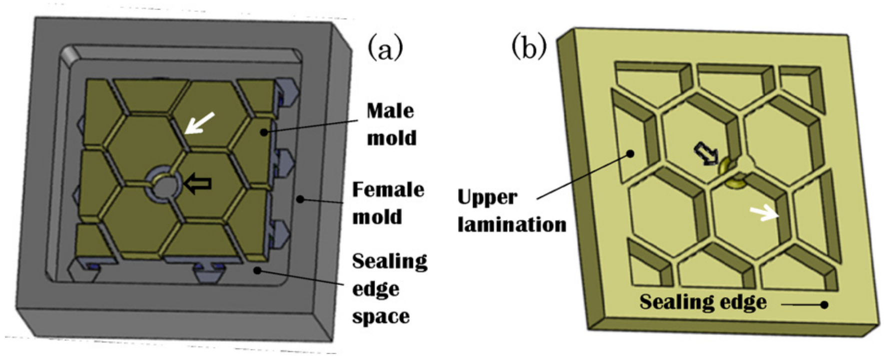

Fig. 7. A schematic of the edge-sealing technology used in the integrated honeycomb. (a) Mold tools for biomimetic sealing and (b) an image of the integrated honeycomb plate with the edge-sealing technology. ⇨ : a trabecula or the space used to form it, → : a honeycomb wall or the space used to form it.

additionally, short basalt fibers are distributed throughout the structure, whereas the long basalt fibers are distributed only within the upper and lower laminations. Although the fibers were not perfectly aligned in the fabricated sample, as otherwise observed in the biological structures, this platform technology will facilitate more in-depth research and future developmental studies for the production of integrated trabecula–honeycomb structure materials.

For example, as in conventional honeycomb plates (Chen, Guo, et al., 2012; Leng, 2009), edge sealing is required for the integrated plates (Chen, Ni, et al., 2012). Fig. 5(b) illustrates the fully integrated design of the beetle forewing, which does not possess any seams or edge structures. To imitate this design, an extra sealing edge space has been integrated into the female mold (Fig. 7a) to generate the sealing edge present in the honeycomb structure (Fig. 7b) (Chen, Xie, et al., 2012). This is a very simple edge-sealing technique for use in fabricating honeycomb structures. Thus, 3D design software can be used to design alternative approaches to the edge-sealing technique, such as techniques to produce curved, interlocking, 3D connecting, and dynamic docking structures. Additionally, it will be simple to produce a special integrated honeycomb structure that has gradient configurations (Lira & Scarpa, 2010; Lira, Scarpa, & Rajasekaran, 2011). As a result, this technology could be used to produce both finished and semi-finished products with easy assembly properties, including smaller structures, such as dinner tables, and larger structures, such as aircrafts or the hulls of ships.

In short, the fabrication technology used to produce the integrated honeycomb panel was developed through biomimetic engineering and can be easily incorporated into automated production systems. Furthermore, the mechanical properties of the finished products are superior to earlier honeycomb technologies due to their high structural integrity. Because the use of adhesives is no longer needed to combine the upper and lower laminations, this technology eliminates the safety and environmental issues typically associated with the use of adhesives. This honeycomb structural technology can be widely used for cellular structural applications requiring a certain sheet thickness, which has the potential to reduce resource consumption, is environmentally friendly and has other social and economic benefits.

4. Conclusions and prospects

Extensive work on the forewings of *A. dichotoma* and *P. inclinatus* has shown that the beetle forewing is a highly optimized biological structure. The forewings of both beetle species involve lightweight integrated frame structures, which consist of central void regions and distributed trabeculae; the forewing of *A. dichotoma* is a lightweight honeycomb structure, whereas the forewing of *P. inclinatus* is more durable. The origin of these observed structural differences may reside in the 10-fold difference between the life spans of the two species. The male *A. dichotoma* utilizes its horn structures to attack and to defend itself; because it has a life span of only several weeks, its forewings are only required to be thin and extremely lightweight. In the female *A. dichotoma*, however, the forewings are predominantly used for self-defense. Additionally, the forewings of female *A. dichotoma* must be stronger than those of the males for breeding purposes. Therefore, the elegant, lightweight, and high-strength design of the beetle forewings are clearly demonstrated in this species.

According to the findings of previous work, biomimetic applications of beetle forewings should consider the possibility of structural variations (i.e., the lamination stacking orientation) by sex to obtain more accurate scientific conclusions and a greater degree of biomimetic inspiration. Specifically, this work has revealed that the beetle forewing is constructed of an integrated honeycomb panel structure and not merely a conventional honeycomb. In the field of biomimetics, beetles are to honeycomb panels as dragonflies are to airplanes and as bats are to radar. Using this work, a platform technology has been developed for the fabrication of an integrated trabecula–honeycomb structural panel. Similarly, the forewing of *P. inclinatus* is a durable, lightweight, and high-strength structure that consists of a trabecular core; this structure may potentially represent a new biomimetic model for developing an integrated, durable, lightweight, and high-strength core trabecular structure. Our success in fabricating integrated biomimetic structures is the first of its kind in the history of traditional assembly methods for honeycomb structures and has paved the way for the development of un-bonded honeycomb structures.

Acknowledgements

This work was supported by the Natural Science Foundation of China (Grant No. 51173026) and the Jiangsu NSF (No. BK2010015).

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