Chapter 4
Insect-Inspired Architecture: Insects and Other Arthropods as a Source for Creative Design in Architecture

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Abstract Materials, structures, surfaces and buildings of insects and other arthropods are of great scientific interest. Moreover, basic knowledge about the functional principles of these structures is also highly relevant for technical applications, especially in architecture. Some of the greatest challenges for today's architecture are multifunctionality and sustainability. Insects have solved these problems during their evolution. Zoologists, entomologists and animal morphologists have collected a huge amount of information about the structure and function of such living constructions and surfaces. This information can be utilized in order to mimic them for applications in architecture. The main technology areas, in which insect solutions to problems can be applied, are the following: (1) new materials, (2) constructions, (3) surfaces, (4) adhesives and bonding technology, (5) optics and photonics. A few selected examples are discussed in this chapter, but having more than one million described species as a source for inspiration, one may expect many more ideas from entomology for insect-based biomimetics in architecture. The incorporation of additional biological knowledge into the design of artificial systems will improve their performance. However, biologists still do not have a complete understanding of how insect materials are constructed, what their performance is, how insect surfaces function, etc. Hence, many technological areas will benefit from additional entomological research. Additionally, most of the huge variety of insects and their systems have been not previously studied at all. This is the reason that the screening for new systems with interesting properties in biology seems to remain an extremely important research field in the near future.

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4.1 Introduction

Insects are among the most diverse groups of animals on Earth, including more than a million described species and representing more than half of all known living organisms (Chapman 2006). The number of extant species is estimated to be between six and ten million (Erwin 1982, 1997; Novotny et al. 2002; Chapman 2006) and approximately represents over 90 % of animal life forms (Erwin 1982). Insects can be found in nearly all environments. During their evolution, insects and related arthropods have evolved a huge variety of shapes and structures. Despite often looking miniature and fragile, they can nonetheless deal with extreme mechanical loads. Many functional systems responsible for their evolutionary success are based on a variety of ingenious materials and structural solutions. The rich sensory equipment of insects, including their compound eyes, chemoreceptors, mechanoreceptors and infra-red (IR) receptors, taken together with their rather compact brain reveals self-adaptive control patterns and often supports remarkable behavioral features.

Studies revealing the functional principles of insect structures, materials, sensors, actuators, locomotion and control systems are, on the one hand, of major scientific interest, since we can learn about the mechanisms behind the structures and their biological roles. On the other hand, this knowledge is also highly relevant for various engineering applications including those in the field of architecture. Two of the greatest challenges for today's architectural designs are energy saving and sustainability. During their evolution, insects and other arthropods have solved many problems dealing with their external lightweight skeleton. Additionally, these animals build a number of remarkable constructions based on silk, glue and surrounding non-living materials (Hansell 2007; Gruber 2011). Zoologists, entomologists and morphologists have collected a vast amount of information about the structure and function of such animal-made buildings and about the materials and structures utilized in their bodies. This information can be used to mimic them for diverse applications in modern architecture. The main fields, in which insect-inspired solutions can be applied to architecture, are as follows: (1) new materials, (2) constructions, (3) surfaces, (4) adhesives and bonding technology, (5) optics and photonics (Fig. 4.1). Possible innovations might also appear on the boundary between insect science and the areas listed above (Gorb 2011). Some selected examples are discussed in this chapter, but with more than one million described species (about one half of the eukaryotic organisms) as a source for inspiration, many more ideas might arise from the study of insects to be used for biomimetics in architecture.

4.2 Buildings and Constructions of Insects

Among the animals capable of building, social insects have the largest workforces to generate complex constructions. Large colonies of social insects with their great overall behavioural complexity build enormous architectures with channels and spaces permeating them and bringing oxygen to their core and carrying carbon

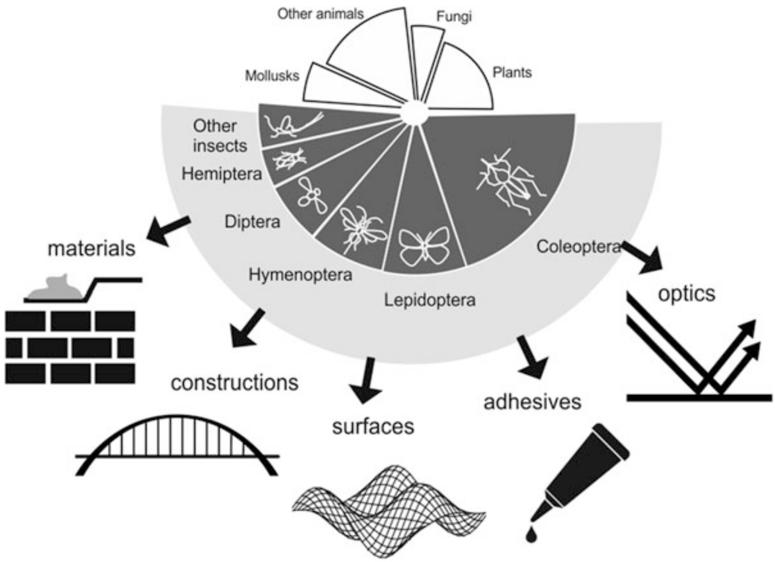

Fig. 4.1 Diagram demonstrating insect diversity (*dark grey* segment of the pie) as a source of biomimetic ideas for application in architecture (Adapted from Gorb 2011)

dioxide away (Hansell 2007). In termite mounds, the multitude of chambers of the living area is linked by apertures and short corridors that can be regarded as the capillaries of the circulation system. These structures produced by termites, for example, have provided inspiration for solar-driven thermoregulating ventilation systems in Europe and Africa. One recent well known example is the ventilation system designed by the company Arup for the East-Gate Hall in Harare, Zimbabwe (Pohl and Nachtigall 2015).

Honeycomb structures occur often in nature and can be actively constructed by mostly social insects such as bees and wasps from completely different materials, e.g. wax and paper. This geometrical pattern is well known to represent the most densely packed units in two-dimensional space, which is an interesting principle for its implementation in architecture. Technical honeycomb structures can be made of a stronger variety of materials, such as plastics, ceramics and metals, and by using a diversity of processing techniques, such as the cutting of hexagonal sheets and subsequent gluing, the insertion of strips of glue between the sheets and subsequent stretching or the application of moulding techniques, especially when polymers are used (Gruber 2011; Pohl and Nachtigall 2015). Honeycomb-patterned lightweight materials can be used in architecture for the core of sandwich panels and composite designs. Because of their large surface area, they are interesting for applications as cooling structures.

For example, Dr. Mirtsch GmbH has developed a broad variety of three-dimensional (3D) metal tins having various thicknesses of sheaths. These structures often originate from a highly specific method of production by using self-

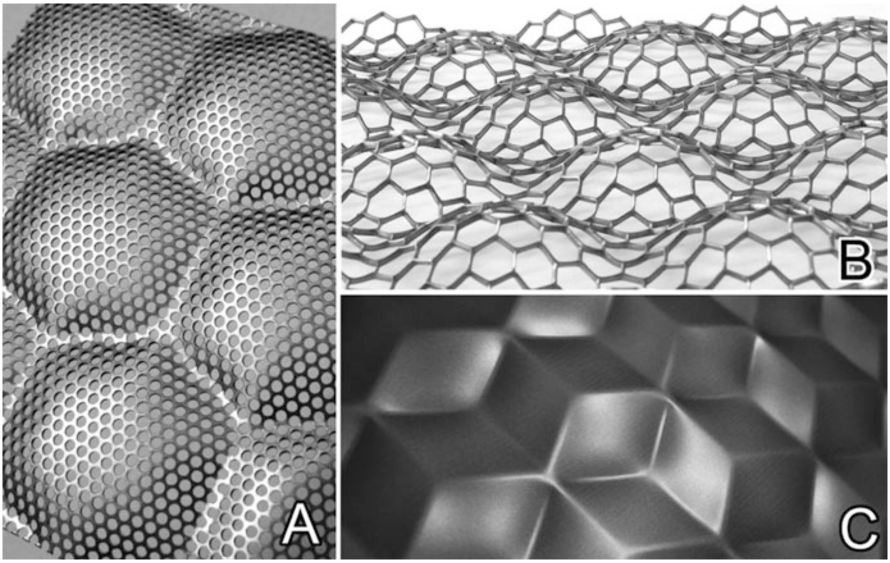

Fig. 4.2 Technical honeycomb structures for use in architecture. Dr. Mirtsch GmbH, Courtesy of Frank Mirtsch (www.woelbstruktur.de)

organization. The structures are rather impressive not just because of their beautiful optical appearance, but mainly due to their convincing technical properties (Fig. 4.2). Among their functional features, the most striking are (1) much stronger bending stability at much lower material use (ultra-lightweight), (2) enhanced crash-resistance properties attributable to stronger energy dissipation, (3) further enhancement of bending stiffness because of their combination into sandwich-like structures, and (4) their ability for combination with other, also dissimilar, materials.

Numerous honeycomb constructions can be found in external facade architecture (Gruber 2011; Pohl and Nachtigall 2015). However, honeycombs are also widely used in interior architecture, such as The Hive (Ben Huckerby Design by Kyle Minnock) (Minnock 2016). The sources of inspiration for this design were the structures, forms and characteristics associated with insects. The project involved not only in-depth research into the structures of honeybee combs, but also a large amount of practical experimentation with card models and other craft materials. Experimentation with light, form, colour and texture was also carried out to achieve the final concept (Minnock 2016) (Fig. 4.3).

Many insects (Lepidoptera, Trichoptera, Hymenoptera, Neuroptera) and other arthropods construct silky shells called cocoons (Fig. 4.4a, b). Usually, larval insects do this in order to additionally protect their pupal stage. In insects, silk is usually produced by labial glands located in the region of the mouthparts. Cocoons can be soft or rigid, dense or loose, and have diverse colours and numbers of layers. Cocoons are also used by spiders, but mainly for egg clutch protection. Spider cocoons are typically two-layered: the inner layer is softer, whereas the external one is more rigid. Additionally, orb-web spiders wrap their prey items in cocoon-like

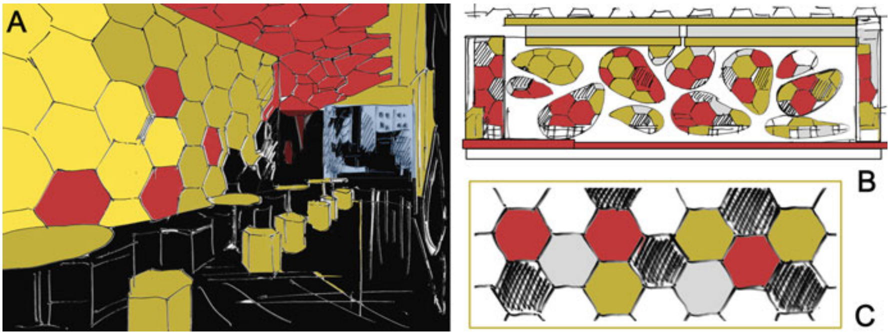

Fig. 4.3 The Hive, insect-inspired interior architecture by Kyle Minnock, Leeds, United Kingdom (Minnock 2016)

shells to prevent prey mobility, especially, when the prey is larger than the predator itself.

The water spider *Argyroneta aquatica* spends most of its life under water. It constructs a special reinforced kind of web construction that holds an air bubble underwater and provides a safe and stable habitat for the spider. First, the spider builds a horizontal sheet web, under which the air bubble is placed. In a further step, the air bubble is sequentially reinforced by the spider laying a hierarchical arrangement of fibres from within (Fig. 4.4c). Such a two-layered construction is stable and can withstand mechanical stresses caused by water currents.

The underwater construction of the water spider and its natural production process show the way that adaptive fabrication strategies can be utilized to create efficient fibre-reinforced structures. The ICD/ITKE Research Pavilion 2014–2015 was inspired by this biological prototype. The pavilion demonstrates the architectural potential of a novel building method. A new robotic fabrication process was developed by using an initially flexible pneumatic formwork that was gradually stiffened by reinforcement with carbon fibres from the inside (Fig. 4.4d–g). The resulting lightweight fibre composite shell forms a pavilion with unique architectural qualities.

This design concept is based on the study of biological construction processes for fibre-based structures. In biology, fibre-reinforced structures are made in a highly material-effective and functionally integrated way. The prototypical project at the ICD/ITKE was the result of 1.5 years extensive development by researchers and students of architecture, engineering and natural sciences. The process developed in this project is of high relevance for applications in architecture, as it does not require complex formwork and is capable of being adapted to the various demands of individual constructions.

In order to transfer the biological way of building to the application in the architecture, a novel process was developed: an industrial robot was placed within an air-supported membrane envelope made of the polymer ethylene tetrafluoroethylene (ETFE). This inflated soft shell was initially supported by air pressure and gradually reinforced from inside with carbon fibre by using the robot (Fig. 4.4d, e). The

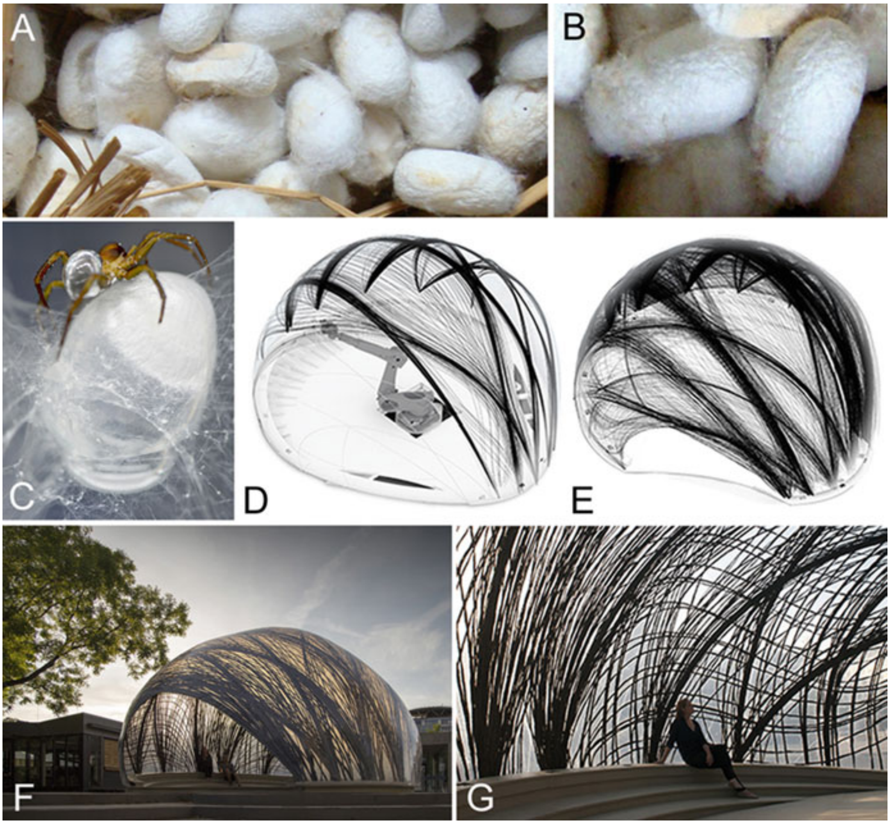

Fig. 4.4 Silk-based arthropod constructions and the use of similar concepts in architecture. (**a**, **b**) Cocoons of the silkworm *Bombyx mori*. (**c**) Air-filled bell-like underwater construction of the water spider *Argyroneta aquatica*. (**d**–**g**) The ICD/ITKE Research Pavilion 2014–2015 designed by the Institute for Computational Design (ICD) and the Institute for Building Structures and Structural Design (ITKE) at the University of Stuttgart was inspired by the silky construction of the spider. (**c**–**g**) Courtesy of ICD and ITKE, Stuttgart, Germany

construction gradually stiffened into a self-supporting monocoque structure. The carbon fibres were only selectively applied, wherever they were required for structural reinforcement. The pneumatic formwork was used at the same time as a functionally integrated building skin.

4.3 Arthropod Skeleton Is Fibre-Reinforced Composite

The continuous external skeleton (exoskeleton) of arthropods is made of chitin fibres embedded in a protein matrix (Hepburn 1985). The chemical, structural and mechanical properties of such a composite material can vary to a large extent and, thereby, allow local functional adaptations in the different areas of the insect's body (Hepburn and Chandler 1976, 1978; Vincent and Wood 1972; Vincent 1981).

The arthropod exoskeleton is an interface between a living animal and the environment and, therefore, serves many functions. (1) It limits the dimensions of the exoskeleton and is a basis for muscle insertion (mechanical function and function of locomotion). (2) It is an important element in organism defence against a variety of external factors, such as mechanical stress and dry, wet, cold or hot environments. (3) It takes part in the transport of diverse epidermal secretions and serves as a chemical reservoir for the storage of metabolic waste products. (4) A variety of cuticular structures are parts of mechano- and chemoreceptors. (5) The cuticle, its coloration pattern and chemical components are important for thermoregulation and are often involved in diverse communication systems. (6) Specialized cuticular protuberances might serve a variety of functions, such as oxygen retention, food grinding, body cleaning (grooming), etc. (see below).

Cuticle is a layered composite material (Fig. 4.5) that consists of two principal components: chitin and protein. The arrangement of chitin molecules usually varies within its different morphs. Chitin microfibrils are always associated with protein in a chitin-protein complex. Chitin-bearing cuticular microfibrils have a complex pattern of orientation in the 3D space of the cuticle. Some types of cuticle are rather stiff and others, such as arhtrodial membranes, are flexible.

Arthrodial and caterpillar-like cuticles are materials of great flexibility, great extensibility and reasonable strength. The interaction between microfibrils and protein matrix is very loose here. Under tension, these cuticles are visco-plastic and show so-called «necking», as do steel specimens under the same conditions

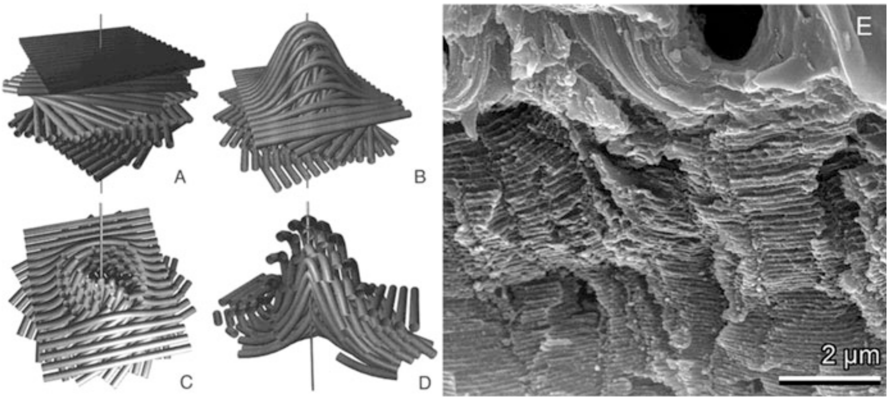

Fig. 4.5 Insect cuticle structure. (**a**–**d**) Model of the orientation of the microfibrils within one lamella in the helicoidal flat cuticle (**a**) and in the helicoidal cuticle of a surface outgrowth (**b**–**d**) (**b**) The whole model of fibre orientation in such a cone helicoid. (**c**) Transverse section of the cone helicoid. (**d**) Longitudinal section of the cone helicoid (Gorb 1997a, b). (**e**) Fracture through the cuticle containing surface microstructures at the rear side of the head in the dragonfly *Aeshna mixta*. Note the layered structure of the exocuticle, which forms such a cone helicoid as depicted in **b**–**d** (Gorb 2011)

(Hepburn and Chandler 1976). However, remarkable variation exists with regard to the extent, to which such cuticles can be extended (Vincent and Wood 1972). Some of these membranous cuticles are strongly folded, such as those found in the abdominal membranes of the tsetse fly *Glossina morsitans* (Hackman and Goldberg 1987) or in the neck membrane of adult dragonflies (Gorb 2000).

Insect cuticle demonstrates, in various functional systems, a gradient of material properties that can range from very stiff areas of the condyli of joints to membranous areas between leg segments. These gradients depend on the fibre density, fibre orientation, polymerization degree of the matrix and thickness of single layers.

Currently, composite materials are widespread in various areas of technology. However, the fibre diameter remains at the range of few micrometers. They also normally have random or preferable orientation within the matrix. Insect cuticle may inspire engineers, for example, with its helicoidal arrangement of fibrils in successive layers and with its gradient-like materials properties. Moreover, fibre orientation in insect cuticle often depends on the local structure geometry (Figs. 4.5 and 4.6a, b). Natural materials, therefore, consist of only a few basic components that are geometrically, physically and chemically differentiated and, in this respect, they are fundamentally different from most architectural constructions (Knippers and Speck 2012). This is the reason that the specific fibre orientations found within insect structures might inspire novel constructions in architecture.

A good example of local geometry-dependent fibre orientation is the architecture of the pore channel (Fig. 4.6a) used by architects and engineers as an inspiration for novel types of building construction. The ICD/ITKE Research Pavilion 2013–2014 (Dörstelmann et al. 2014; Parascho et al. 2014) is the result of multidisciplinary research. A strategic pre-selection of biological models based on natural lightweight fibre structures with specific anisotropic features preceded the project (Fig. 4.6a, b). Natural fibre composite structures, surrounding channels in insect cuticle, such as those of the elytra (protective forewing) in beetles, provided a versatile model for performative lightweight structures (Dörstelmann et al. 2014). The material efficiency of the system is based on the anisotropic organization of chitin fibre composite material, which forms a kind of double-layered shell (Figs. 4.6c and 4.7).

Biological architecture, which is present at the micro- and nanoscales, has been translated to the macroscale. Various fibre orientations surrounding the hole not only stabilize the entire construction, but additionally prevent stress concentration in the hole. This kind of architecture not only is visually beautiful, but provides enormous stability at the minimum material expenditure in spite of the presence of holes. On the material scale, structural integration is achieved through the use of continuous fibre.

4.4 Folding Mechanisms

Insect wings are usually thin and delicate outgrowths of the body wall. In order to prevent their damage, some groups, such as beetles, earwigs or bugs, have fore wings that serve a protective function and are therefore thickened and stiff. The hind

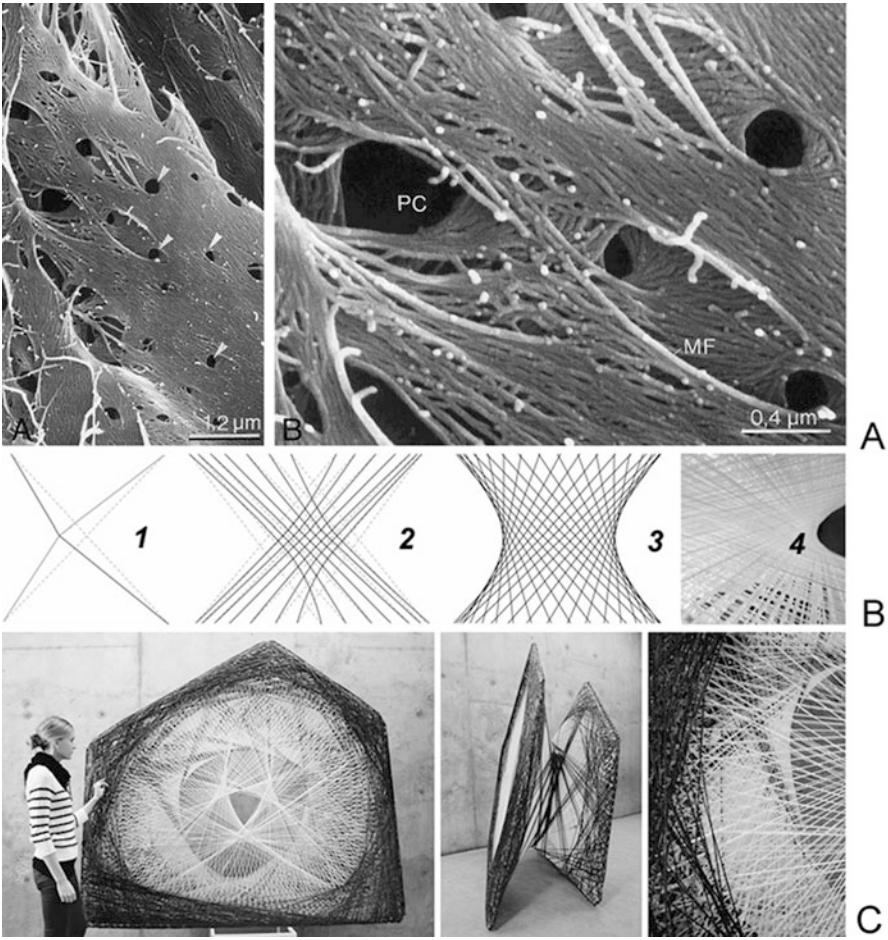

Fig. 4.6 (**a**) Microfibril orientation around the porous channels in the insect cuticle (scanning electron micrograph): *MF* microfibrils, *PC* and *white arrowheads*, porous channels (Gorb 1997a, b). (**b**) Coreless winding: (*1*) two fibres connecting four non-planar points; (*2*) fibres deforming under the tension of subsequently wound fibres; (*3*, *4*) anticlastic curvature induced by helicoidal winding. (**c**) Single component and fibre detail (Dörstelmann et al. 2014; Parascho et al. 2014). (**b**, **c**) Courtesy of ICD and ITKE, Stuttgart, Germany

wings must exhibit a certain area in order to be aerodynamically functional and they are indeed larger than the thickened forewings. The only possibility for the hind wings to be completely covered by the fore wings is to be folded (Haas et al. 2000a) (Fig. 4.8a–c).

The folding pattern depends on the wing venation pattern and the material properties of the structures involved. Consequently, the morphology of wings in insects with an additional folding function differs from the wings without the folding capability. The design of foldable wings is a compromise between flight and folding (Haas et al. 2000b). For example, the hind wings of earwigs (Dermaptera) are strongly folded and covered by the small, thickened and sclerotized fore wings. The

Fig. 4.7 ICD/ITKE Research Pavilion 2013–2014 (Dörstelmann et al. 2014; Parascho et al. 2014) inspired by fibre orientation around pores in insect cuticle. Courtesy of ICD and ITKE, Stuttgart, Germany

area of the unfolded wing is ten times larger than that of the folded wing (Haas et al. 2000a). The folding pattern in earwigs is rather complicated and is made possible by the combination of muscle activity, the pleating pattern, and the specific distribution of resilin, a rubber-like protein, within the folds (Fig. 4.8d).

A specific pleating pattern is responsible for high elasticity of the wing. Three-dimensionally pleated wings have an asymmetric torsional rigidity (Wootton 1991). Another mechanism is based on a gradient-like distribution of the rigid and soft resilient materials of the thin membranous areas of wing cells (Haas et al. 2000a, b).

Pleated structures are widely used in architecture (Gruber 2011) because of their flexural rigidity and lightweight properties. However, the number of real functional folding constructions in architecture is not that high. One great example of such a kinematic structure is the three-field Bascule Bridge in Kiel Horn, Germany (Fig. 4.9a–c). The bridge is moved through a complex cable system of numerous ropes, winches and rollers and, simultaneously, each change to the construction's position has to be stabilized to counteract wind loads potentially coming from all directions (Knippers and Schlaich 2000; Knippers and Speck 2012). The architectural intent was to incorporate real folding mechanics and its functionality. However, this bridge is a unique item: it was planned and built

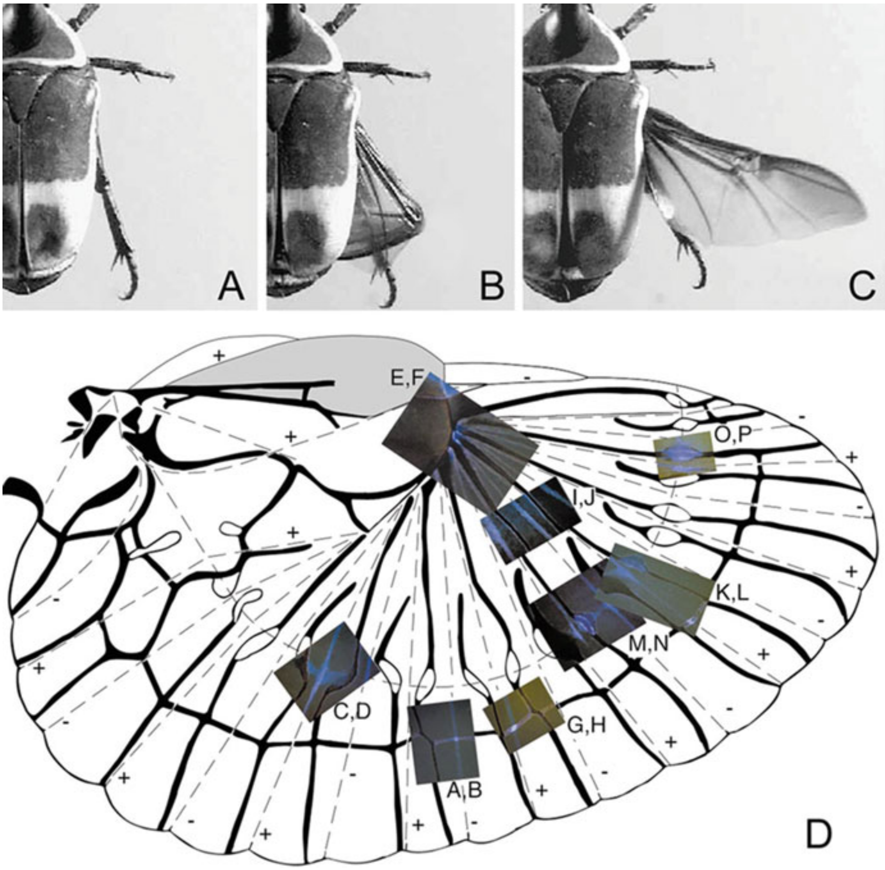

Fig. 4.8 Insect wings folding structures. (**a–c**) Beetle *Pachnoda marginata*, single frames from a video sequence of the wing unfolding (from Haas et al. 2000b). (**d**) Distribution of resilin, a rubber-like protein, in a hind wing of the earwig *Forficula auricularia*. Blue autofluorescence shows the presence of resilin (From Haas et al. 2000a)

without any reference projects or prototypes (Knippers and Speck 2012). This means that the design of the bridge was not inspired by biology, although an increasing amount of data from the mechanics of biological folding structures might help to improve the robustness, reliability and appearance of such structures in architecture.

Another interesting example of folding structures is the Zoomlion Headquarters Exhibition Center located in the city of Changsha, Hunan Province, China (Fig. 4.9d–f) (AmphibianArc 2012). The total building height is 26 m. Since Zoomlion is one of China's leading manufacturers of heavy machinery equipment, one of the criteria for the design of its exhibition centre was the incorporation of nature-inspired mobility into its architecture.

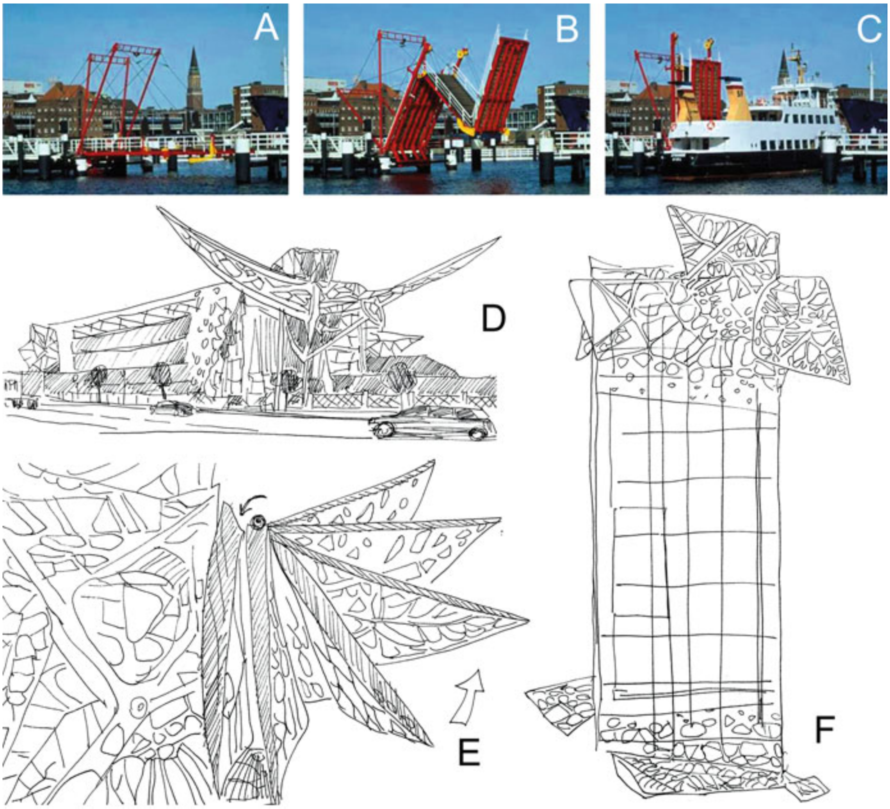

Fig. 4.9 Folding structures in architecture. (**a**–**c**) Folding bridge in Kiel (1998). Architect: von Gerkan Marg and Partner; Engineer: Schlaich Bergermann and Partner (photo: Klaus Frahm, from Knippers and Speck 2012). (**d**–**f**) The project Zoomlion Headquarters Exhibition Center for the city of Changsha (Hunan Province, China) by amphibianArc (AmphibianArc 2012)

The skin of the building is made of steel and glass. The most unique aspect of the project is the building's ability to change shape. The double skin system throughout the building is responsible for this transformability. The inner skin takes care of the enclosure and building systems, whereas the outer one contains controllable portions that can be opened or closed to mimic various animal forms, including that of a butterfly (AmphibianArc 2012). This reflects the company's philosophy of maintaining a balance between nature and technology. The façade is inspired by the wing constructions of insects such as butterflies and dragonflies. To achieve the systematic and organic nature of the patterns found on the wings of these insects, the architects used parametric modelling tools to generate and design the façade (AmphibianArc 2012).

4.5 Surfaces and Textures

Insect surface structures can serve many different functions, such as air retention, food grinding, body cleaning, etc. (Fig. 4.10). Some examples of these surfaces seen in a scanning electron microscope are given in Fig. 4.11.

Because of the structural and chemical complexity of insect surfaces, exact working mechanisms have been studied in only a few systems. Due to a broad diversity of surface functions, inspirations from entomology are currently in focus in a broad range of research topics in the engineering sciences including adhesion, friction, wear, lubrication, filtering, sensorics, wetting phenomena, self-cleaning, anti-fouling, thermoregulation, optics, etc. Since insect surfaces are multifunctional, it makes them even more interesting from the perspective of potential applications in architecture. In Fig. 4.11, we see a rather unspecialized polygonal surface on a beetle tarsus (a), anti-reflectors in the fly (b), self-cleaning scales on the dorsal surface of the beetle (c–d), drag-reducing wing surface of the fly (e), food filter of the fly (f), respiratory filter of the beetle (g), grinding teeth in the fly (h) and air retaining coverage in water bugs (i, j) (Gorb 2011).

One of the challenges in the design of moving parts is the fabrication of joints allowing the precise motion of parts about rotational axes. An important problem in any type of mobile joint is the high friction and wear rate. Wear of the interacting surfaces is a consequence of friction and affects the material's contact points by their becoming deformed or being torn away. Friction and wear are strongly correlated processes, by which the points of the surfaces that are in contact change their topography continuously. Conventional methods of lubrication cannot always be used. Friction reduction in some man-made mechanical systems is based on the different hardness of the elements in contact (Miyoshi 2001, Li et al. 2004), on

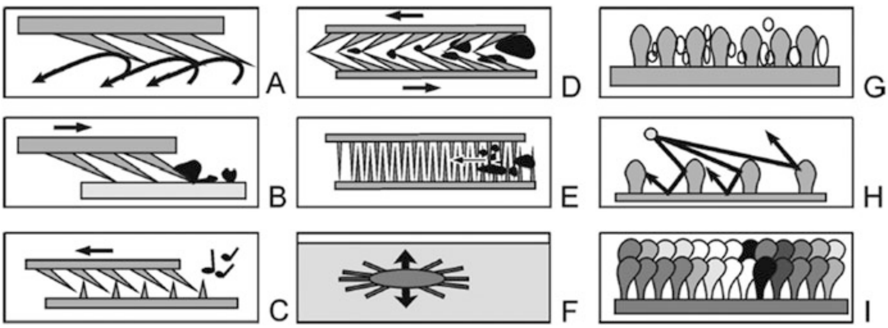

Fig. 4.10 Diagram of functions of cuticular microstructures in insects. (**a**) Aerodynamically active surfaces. (**b**) Grooming. (**c**) Sound generation. (**d**) Food grinding. (**e**) Filtration. (**f**) Hydrodynamically active surfaces. (**g**) Air retention. (**h**) Thermoregulation. (**i**) Body coloration pattern (Gorb 2001)

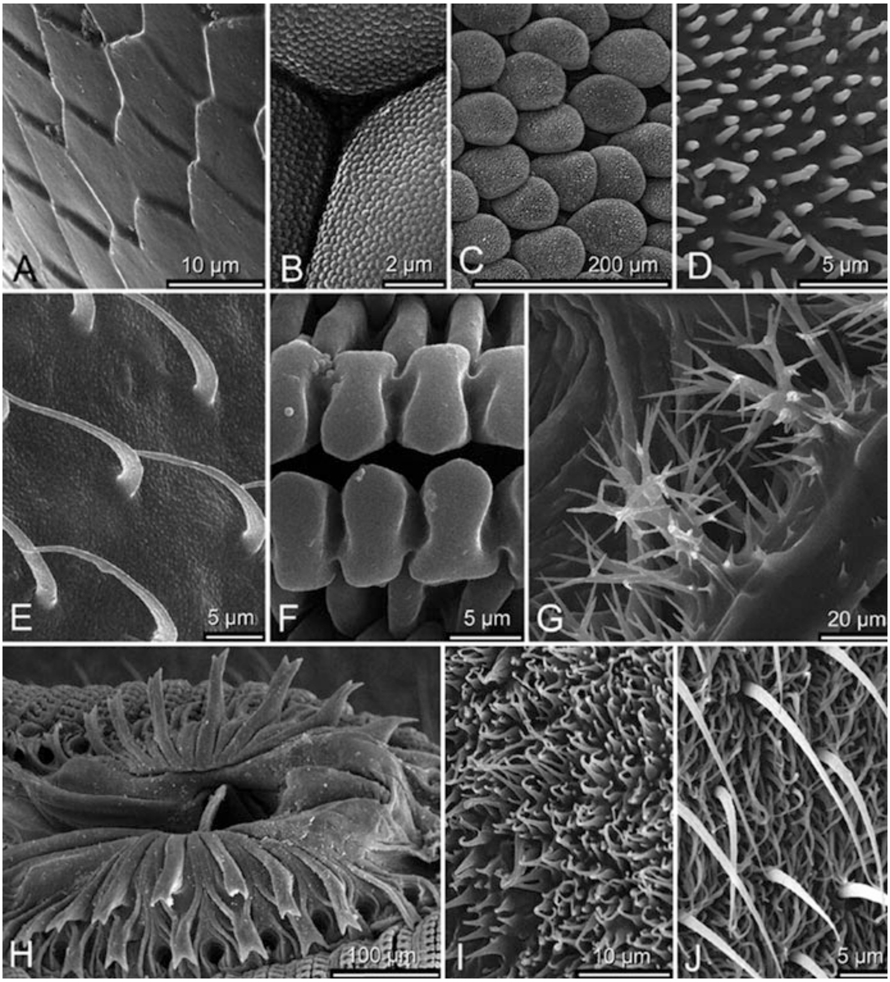

Fig. 4.11 Functional diversity of non-innervated cuticular protuberances in insects. (**a**) Unspecialized polygonal surface on the tarsus of the scarabaeid beetle *Melolontha melolontha*. (**b**) Ommatidial surface in the calliphorid fly *Calliphora vicina*. (**c**) Scales on the dorsal surface of the elytron in the scarabaeid beetle *Hoplia sp*. (**d**) Same; the surface of a single scale. (**e**) Wing surface in the bibionid dipteran *Bibio ferruginatus*. (**f**) «Pseudotrachea» of the labellum in *C. vicina*. (**g**) Filter system of the spiracle in the tenebrionid beetle *Tenebrio molitor*. (**h**) Prestomal teeth in *C. vicina*. (**i**) Plastron in the nepid bug *Ranatra linearis*. (**j**) Air-retaining hair coverage in the water-strider *Gerris lacustris* (Gorb 2011)

the use of hydrophobic surfaces, and on the application of surface texture, which minimizes the real contact area between two solid surfaces. Ideas from studying the surface properties of insect joints, which have stiffer outer layers located onto softer ones (Fig. 4.12b, c, e), the specialized microstructure covering the contact

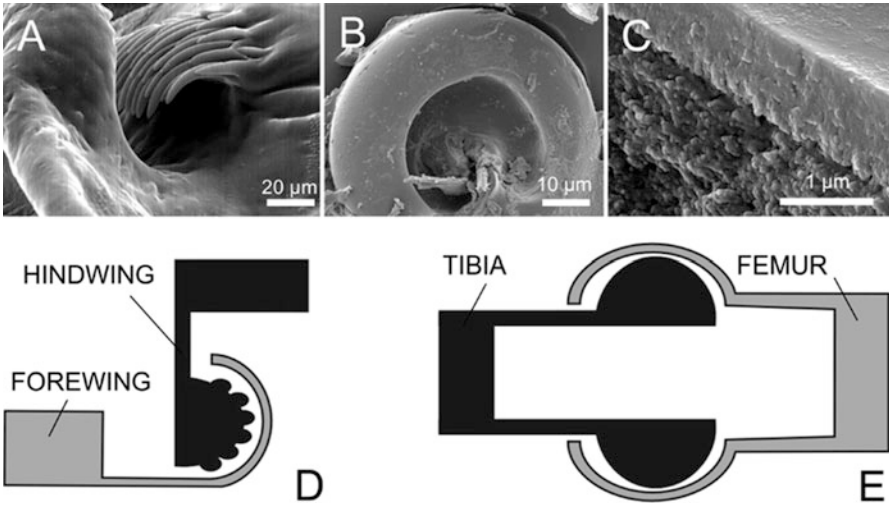

Fig. 4.12 Examples of micro-joints in insects. (**a**) Lateral view of the wing double-wave locking mechanism in the bug *Coreus marginatus* (forewing part). This is a monoaxial sliding joint that provides interlocking between both wings on the same side of the body in the anterior direction allowing them to slide in the medial and lateral directions (Perez Goodwyn and Gorb 2004). Sliding is possible along the axis perpendicular to the plane of the image **a**, whereas the motion is restricted in all directions in the plane of the image. (**b**) Medial aspect of the monoaxial rotating femoro-tibial joint (femoral part) of the leg in the beetle *Melolontha melolontha*. Rotational movement is possible about the axis perpendicular to the plane of the image **b**, whereas the motion is restricted in all directions in the plane of the image. (**c**) Fracture of the material of the joint in the beetle *M. melolontha*. (**d**) Diagram of the sliding joint shown in **a**. (**e**) Diagram of the femoro-tibial joint shown in **b** and **c** (Gorb 2011)

pair (Fig. 4.12a, d), and the particular fibre orientation in exocuticle might provide an interesting set of principles leading to a solution of this problem (Perez Goodwyn and Gorb 2004; Barbakadse et al. 2006).

In insect joints working under lower loading forces, but much higher frequencies than vertebrate joints (Wootton and Newman 1979; Gronenberg 1996), the joint surfaces usually present a combination of wavy and smooth counterparts (Fig. 4.12a, d).

Insect surfaces are often covered by a superhydrophobic (non-wettable by water) cuticle that has an external layer consisting of both cuticle microstructure and/or epicuticular waxes. The layer may contain wax projections with dimensions ranging from hundreds of nanometers to micrometers (Fig. 4.13). The roughness of such surfaces together with their hydrophobic properties decreases wettability, which is reflected in a greater contact angle of water droplets on such surfaces compared to smooth surfaces of the same chemical composition. In some plant surfaces, this property results in their ability to be cleaned by rolling drops of water (Barthlott and Neinhuis 1997, 1998). Similar insect structures, such as those on the wings

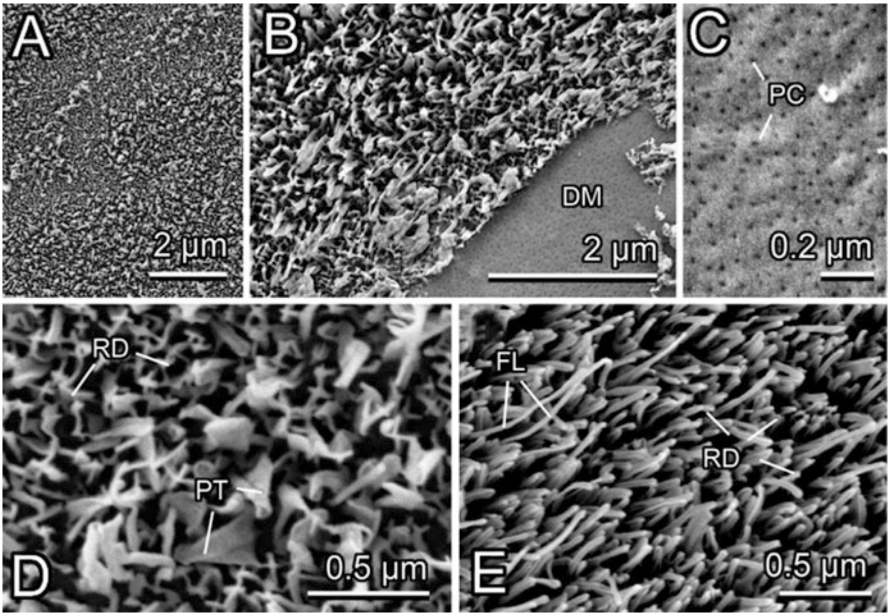

Fig. 4.13 Dorsal wing surface of the dragonfly *Calopteryx splendens*: young mature male surface of wing membrane covered with crystalline wax (**a**, **d**, **e**); wing membrane surface with damage (scratches) in the wax crystalline layer (**b**, **c**). *DM* damage/scratch, *FL* wax filaments, *PC* porous channels of cuticle, *PT* wax platelets, *RD* wax rods (Gorb et al. 2009)

of representatives of Odonata, Ephemeroptera and Neuroptera, are extremely non-wettable and self-cleaning (Wagner et al. 1996). Superhydrophobic coatings are widespread nowadays in modern architecture. One of the most recent examples is the so-called Lotus House in Daegu, South Korea, designed by smart architecture (Daegu) (Baunetz 2015). The name actually originates from the perforated walls resembling the lotus flower, but the self-cleaning superhydrophobic surface completes the impression of this famous plant.

Many aquatic and semiaquatic arthropods have sculptured surfaces involved in holding air under water for respiration. Such surfaces called plastrons usually contain fields of microtrichia, i.e. very small cuticle protuberances (Heckmann 1983). These structures appear convergently as an adaptation to aquatic environments in various arthropod taxa: Collembola, Lepidoptera, Coleoptera, Heteroptera, Diptera, Araneae and Diplopoda (Thorpe and Crisp 1947; Hinton 1976; Messner 1988). Some terrestrial insects, such as Aphididae (Auchenorrhyncha), also bear similar features in the form of bristles, mushroom-like spines or stigmal plates, which can protect their surfaces from moisture (Heie 1987). In water striders and some spiders, the anti-wetting surfaces of their legs and the ventral body side are involved in the locomotion mechanism of walking on water.

Dragonflies, which can spend quite a long time underwater and take off directly from the water surface, have elaborate stable superhydrophobic coatings on their entire body (Gorb et al. 2009) (Fig. 4.13). However, the most stable air-holding surfaces are known from strongly specialized aquatic bugs from the genera *Halobates* (Gerridae) and *Haloveloides* (Veliidae), the only open sea water dwellers (Perez Goodwyn 2009). Representatives from the genus *Halobates* have outstanding water protection structures. The microtrichia pile is composed of specialized prolongations. Each microtrichium has a thickened head, which is several times wider than the shaft and usually tilted to one side like a golf club. On the shaft itself, up to four perpendicular branches interlock the microtrichia, the shafts of which are 0.8–1.1 μm apart. Such surfaces, which can prevent wetting for a long time, are of interest for underwater buildings (Mazzoleni 2013) and in naval architecture (Tupper 2013).

Surface outgrowths can provide the multi-level reflection of sunlight. Such an ability of wing scales has been suggested to be an adaptation for cooling in butterflies (Grodnicky 1988). Body coverage by bristles, scales and hairs in the honey-bee *Apis mellifera* might be used for warming up (Southwick 1985). In species of curculionid beetles of the genus *Tychius*, which inhabit arid areas, cuticular scales have been suggested to be responsible for maintaining thermal balance (Karasev 1989). A water-loss-preventing function has been proposed for the leaf-like bristles at the body margins in Aphididae (Auchenorrhyncha) (Heie 1987).

The surfaces of some desert insects are covered with hydrophobic wax projections that presumably decrease water evaporation through the cuticle and aid in water collection by condensation (Parker and Lawrence 2001). This biomimetic idea is realised in the WarkaWater tower, which has been designed for the Ethiopian landscape (Bamboo Tower 2015). The bamboo-shaped building is designed to harvesting water out of the air, thereby providing a sustainable source of H_2O for developing countries. Created by Arturo Vittori and his team at Architecture and Vision, the tower can harvest water from rain, fog and dew. The WarkaWater functions by using mesh netting to capture moisture and to direct it into a hygienic holding tank accessed via a spout.

Insects provide an enormous amount of interesting textures for building design. Many 3D patterns, such as those observed on the covering wings of the carabid beetles, are almost an unexplored source of inspiration for design in architecture (Fig. 4.14).

Functional surfaces in architecture have many functional requirements that can be fulfilled by using ideas from biology. Since insects bear a huge variety of such microstructures, many of which have not even been previously described, a systematic approach to insect surface science would be highly desirable. An important step in this direction is the establishment of a database of insect functional surfaces. Furthermore, we need more experimental studies targeted to understanding the relationship between structure at various levels of organization and function. We believe that the enhancement of the pool of new ideas from biology will provide a great leap forward with regard to the surface technology of tomorrow.

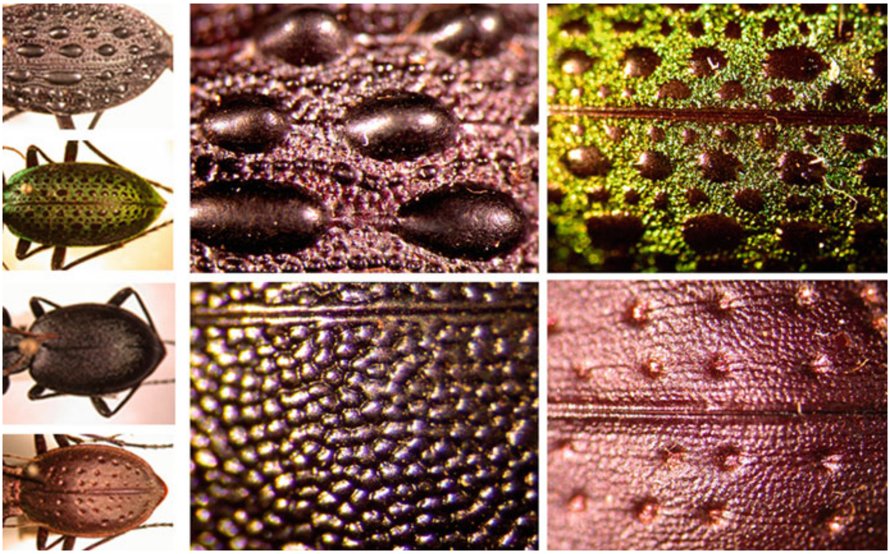

Fig. 4.14 Surface textures of beetles from the family Carabidae for potential implications in architecture and design

4.6 Photonics

Ommatidial gratings are anti-reflective structures on the eyes of insects, especially those that are nocturnally active (Fig. 4.15). These protuberances are very small microtrichia (200 nm in diameter) that increase visual efficiency through decreased surface reflection in their density and increased photon capture for a given stimulus condition (Parker et al. 1998; Vukusic and Sambles 2003). Such a grating is particularly useful on a curved corneal surface, since it increases the transmission of incident light through the cornea compared to a smooth surface. For an increase in transmission and reduced reflection, a continuous matching of the refractive indexes n_1 and n_2 at the boundary of both adjacent materials is highly critical (Bernhard et al. 1965).

Grooming is an extremely important function for insects, some of which live in extremely dirty or dusty environments. Their rich sensory equipment of eyes and antennae has to be kept clean in order to be able to respond adequately to external signals. Many insects bear specialized cleaning structures (Schönitzer and Lawitzky 1987; Francouer and Loiselle 1988). Others rely on micro- and nanostructured surfaces with an anti-adhesive function. Ommatidial gratings are a multifunctional surface that employs self-cleaning by means of a real contact surface reduction mechanism (Peisker and Gorb 2010).

Structural coloration attributable to the presence of scales and bristles is well known in insects, such as butterflies (Ghiradella 1989) and beetles (Schultz and

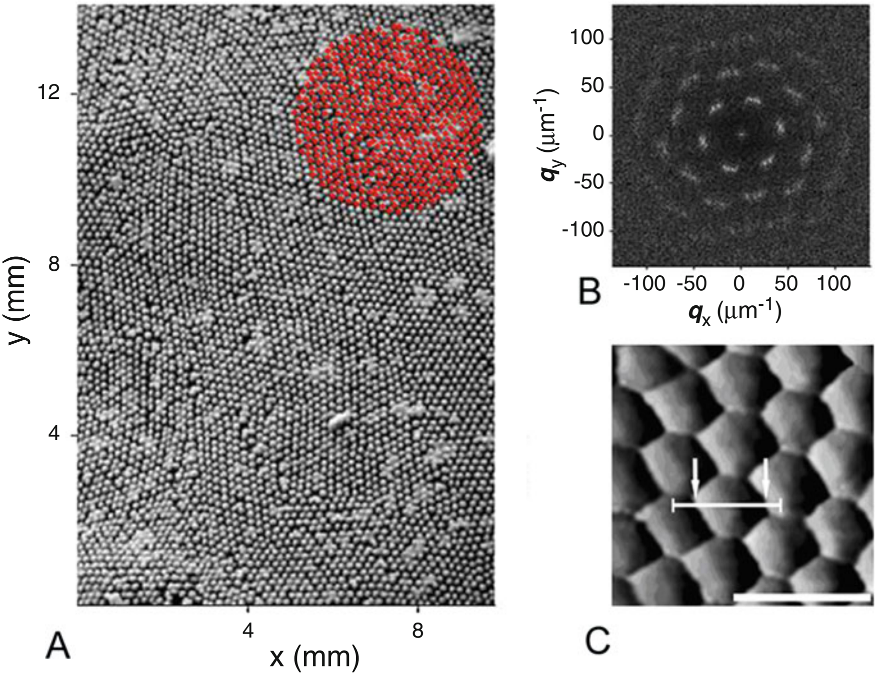

Fig. 4.15 Anti-reflector of the moth eye. (**a**) Scanning electron microscopy image of a single ommatidium surface of an eye in the moth *Manduca sexta*. (**b**) Fourier transformation of the encircled area highlighted in red in (**a**) (Kovalev et al. 2016). (**c**) Atomic force microscopic image of ommatidial nipples of the moth *Laothoe populi*. *White bar* marks the region used to indicate a single nanonipple. *Scale bar* = 500 nm (Peisker and Gorb 2010)

Hadley 1987). For example, scales of some curculionid beetles bear photonic crystals inside scale-like setae on their surfaces responsible for the lusterless appearance of the elytra (Fig. 4.16a–c). The coloration pattern serves for species communication and sex recognition and also for camouflage and mimicry. The most interesting type of structural coloration is called iridescence, which is well known in beetles and butterflies (Ghiradella et al. 1972; Huxley 1975) and has also been recently characterized for some dragonfly species (Gorb et al. 2015; Guillermo-Ferreira et al. 2015a, b) (Fig. 4.16d–f).

The iridescence is a result of optical interference within multilayer structures (Ghiradella 1991) that are rather complex in their architecture and can be incorporated into systems that can produce several different optical effects. Such effects include diffraction-assisted reflection angle broadening (Vukusic et al. 1999, 2000a), all-structural colour mixing and strong polarization effects (Vukusic et al. 2000b). Vinothan Manoharan and his collaborators from the Harvard School of Engineering and Applied Sciences have developed man-made colour technology that never fades (Park et al. 2014). Their innovative method recreates structural

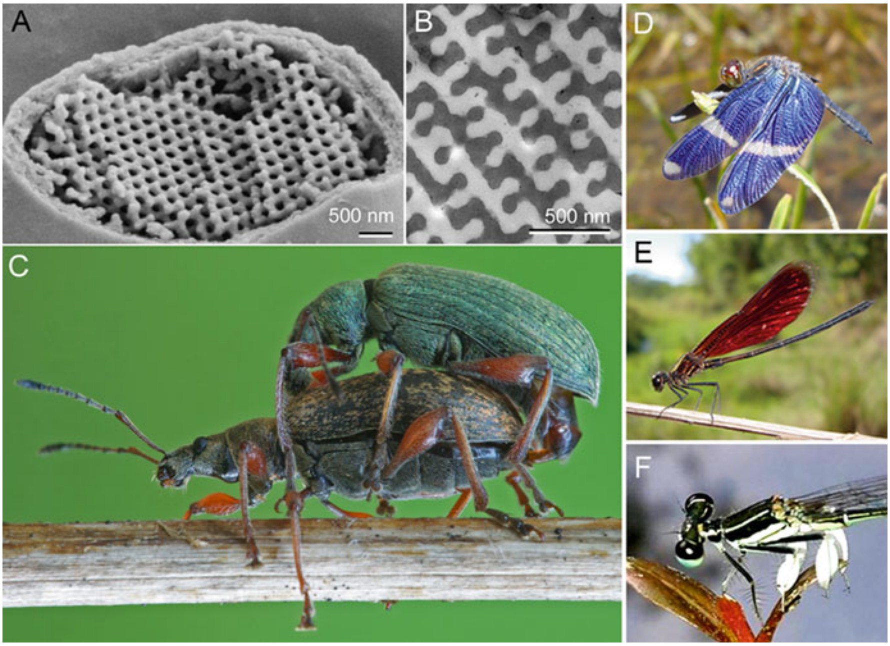

Fig. 4.16 Photonic crystals of the dorsal green scale-like hairs in the male curculionid beetle *Phyllobius argentatus*. (**a**) Scanning electron microscopy micrograph of a cross fracture through the scale. (**b**) Transmission electron microscopy micrograph of an oblique ultrathin section of the scale (Gorb 2011). (**c**) Copulating female and male of *Phylobius* beetles (Image by Marcel Zurreck). (**d–f**) Three different examples of photonic systems in dragonflies: *Zenithoptera lanei* (Guillermo-Ferreira et al. 2015a), *Mnesarete pudica* (Guillermo-Ferreira et al. 2015b), and *Platycnemis phyllopoda* (Gorb et al. 2015)

colours in artificial materials. They fill microcapsules with an aqueous solution of small disordered particles. When the capsules dry out, they bring the particles closer together, producing a colour. Depending on the degree of solvent evaporation, the researchers can produce diverse structural colours for potential use in architecture.

4.7 Adhesives and Bonding Technology

Adobe is a building material made from earth and often organic material, the adhesive properties and strength of which are crucial for the stability of the adobe-based buildings. Adobe was among the earliest building materials and is used throughout the world. Adhesives in general and in architecture in particular currently have three main goals: (1) an increase in the reliability of glued contact; (2) the mimicking of natural environment-friendly glues and (3) the development of mechanisms for the application of a minute amount of glue to the surface (Hennemann 2000). An additional challenge is the use of substances and/or mechanisms that allow multiple attachments and detachments and enable attachment to a variety of surfaces.

The advantages of bonding in architecture in comparison to conventional joining technologies are numerous. Adhesive bonding enables the architect to go beyond the borders of the conventional. In particular, the joining of different materials can only be achieved by means of adhesives. By using bonding, damage to the parts that have to be joined can be greatly reduced. Even the smallest parts and very thin components (e.g. films) can be attached. Reduction of weight can be easily achieved: lightweight construction is possible. However, for two serious reasons, bonding is only used to an extremely limited extent for load-bearing connections. The main reasons are that long-term behaviour (a life time of 50 years is expected for any building construction) is usually not proven and, in the case of fire, capacity is immediately lost. The present section demonstrates some potentials of insect adhesive systems for inspiring the development of technical adhesives for use in the construction of buildings.

A variety of biological systems prevents the separation of two surfaces. These systems are often called *attachment devices* (Gorb 2001). Some of them are mainly based on mechanical principles, whereas others additionally rely on the chemistry of polymers and colloids (Scherge and Gorb 2001; Habenicht 2002). The inspirations from the first type are potentially more suitable for use in architecture. There are at least three reasons for using attachment devices in architecture: (1) they join dissimilar materials, (2) they improve stress distribution in the joint and (3) they increase design flexibility (Waite 1983). These reasons are also relevant to the evolution of natural attachment systems.

Many species of insects are supplied with diverse attachment devices, with the morphology depending on the species' biology and the particular function, in which the attachment device is involved. The evolutionary background and animal behaviour influence the specific composition of attachment systems in each particular species. Eight fundamental classes of attachment principles have been described in insects: (1) hook, (2) lock or snap, (3) clamp, (4) spacer, (5) suction, (6) expansion anchor, (7) adhesive secretion (glue) and (8) friction (Gorb 2001). However, various combinations of these principles also occur in existing attachment structures. Three types of adhesion at the organism level are known: (1) temporary adhesion allowing the organism to attach strongly to the substrate and detach quickly when necessary, (2) transitory adhesion permitting simultaneous attachment and movement along the substrate and (3) permanent adhesion involving the secretion of cement. These three types of adhesion do not have the same purpose and use different adhesive systems.

Insects are capable of walking on smooth and structured substrata, on inclines and vertical surfaces and some of them even walk on the ceiling. For example, flies and beetles rely on the hairy (setose) surfaces on their legs. This system additionally uses a secretion enabling hairs called tenent setae to attach and detach very quickly to diverse substrata. The hair design includes a mechanism that delivers the secretion in extremely small amounts directly to the contact area (Ishii 1987) and only then, when contact to the substrate is achieved. Tenent setae are relatively soft structures

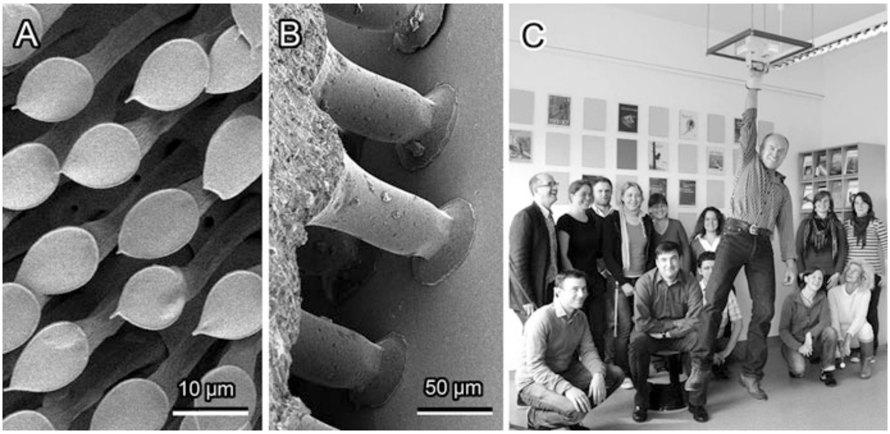

Fig. 4.17 Insect-inspired fibrillar adhesive. (**a**) Ventral surface of the tarsus in the male of the chrysomelid beetle *Gastrophysa viridula*. (**b**) Microstructured polymer foil adhering to a glass surface. Note specific mushroom-shaped geometry of terminal contact elements in both systems (Gorb et al. 2007). (**c**) Demonstration of the performance of the dry adhesive material shown in **b**: A piece of foil of 20 cm × 20 cm can hold about 65 kg weight on the ceiling

(Niederegger et al. 2002). In *Calliphora* flies, their tips are usually compressed, widened and bent at an angle of about 60° to the hair shaft (Bauchhenss and Renner 1977). Some male beetles possess mushroom-like terminal tips on their setae (Fig. 4.17a).

Various forces might contribute to the resulting attachment force: capillary adhesion and intermolecular van der Waals forces. A contribution of intermolecular interaction to overall adhesion has been shown in experiments examining the adherence of beetles (Stork 1980) and beetle setae (Stork 1983) to a glass surface. In the beetle *Chrysolina polita* (Chrysomelidae), the resulting attachment force directly depends on the number of single hairs contacting the surface. The contribution of intermolecular interaction and capillary force has been demonstrated for the fly *Calliphora vicina* in a nanoscale experiment by using an atomic force microscope (Langer et al. 2004). Attachment forces increase, when the contacting surfaces slide against each other. This might be the reason that flies placed on a smooth undersurface always move their legs in a lateral-medial direction (Wigglesworth 1987; Niederegger and Gorb 2003). During these movements, setae slide over the surface obtaining optimal contact.

The size of single points in hairy attachment devices gets smaller and their density higher as the body mass increases (Scherge and Gorb 2001; Arzt et al. 2003). The fundamental importance of multiple micro- and nanoscopical contacts for adhesion on smooth and rough substrata has been demonstrated experimentally (Peressadko and Gorb 2004; Gorb et al. 2007). A patterned surface, made out of polyvinylsiloxane, has significantly higher adhesion on a smooth substrate than a smooth sample made out of the same material. An additional advantage of patterned surfaces is the reliability of contact on various surface profiles and the increased defect tolerance of individual contacts. The forces generated by such a microstructured insect-inspired tape are sufficient to withstand the large forces (Fig. 4.17b, c) required for their use in architecture.

Specific advantages of using insect-inspired glue-free bonding technology in architecture is its good acoustic insulation, protection of bonded surfaces against corrosion, freedom of design, absorption of vibration, compensation of joint tolerances and thermal isolation. This type of adhesive provides a broad variety of customer-specific solutions; this is ideal when a previously existing profile design has to be retained. It guarantees easy installation and removal, while providing maximum adhesion to glass and other smooth surfaces. Easy removal of the tape allows an optimal recycling process.

4.8 Future Perspectives

Statistics shows that American companies generate, on average, 0.5 ideas per employee per year, whereas typical Japanese companies generate 9 ideas per employee per year; both numbers are relatively low. Our creativity is obviously limited. However, we can extend this by employing the great bank of ideas from living nature. Every organism on the Earth has evolved through adaptation and the survival of the fittest and, hence, organisms have retained only those evolutionary adaptations that make them strong.

What can be done to advance architecture by using insect-inspired biomimetics? First and obviously, additional research into insect materials, constructions and surfaces will help in the application of biological knowledge to recent challenges in architecture. The incorporation of additional biological knowledge into the design of artificial systems will improve their performance. Unfortunately, biologists still do not have a complete understanding of how insect materials are constructed, what their performance is, how insect surfaces function, etc. Hence, many technological areas will benefit from additional entomological research. Additionally, a huge variety of insects and their systems have never previously been studied. Screening for new biological systems with interesting properties therefore remains an extremely important research field in the near future.

Some 1.7 million different organisms are known to science. However, all estimations suggest that the actual number of organism on Earth is between 8.6 to over 20 million species: about 90 % of the residents of our planet are unknown. Despite the Convention on Biological Diversity (CBD) and other agreements, loss of habitats and dramatic extinction rates are unchanged or even increasing (see the chapter by Barthlott et al. in this book). We have a responsibility to maintain the idea bank of biodiversity in order to increase the quality of human life, while overcoming the degenerative forces that might destroy organisms and their environment (Hwang et al. 2015). Advances in biomimetics provide an additional reason for carrying this task out because, in doing so, we might harmonize relationships between biological evolution and technological development.

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