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THE WOODPECKER'S BEAK: AN OPTIMALLY DESIGNED STRUCTURE/MATERIAL FOR ENERGY ABSORPTION AND SHOCK MITIGATION

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ABSTRACT

Woodpecker beaks have the ability to absorb shock energy without any damage to their body. In his book Origin of the Species Charles Darwin mentioned that the "woodpecker, with its feet, tail, beak, and tongue, so admirably adapted to catch insects under the bark of trees" in trying to explain how adaptation led to evolutionary changes in the woodpecker. Did the woodpecker with its beak, tongue, tail, and feet really adapt over long periods of evolutionary time or was it designed by its Creator to live in its particular environment and conditions. The analysis in this study shows the intense complexity of the woodpecker's beak arguing for an engineering design by its Creator. In particular, this study focuses on the structure-property relationships of the woodpecker beak at multiple length scales. In particular, the woodpeckers' beaks were examined through microscopy and nano/micro indentation to quantify the structure-property relationships with the perspective of mitigating shock waves. The beak of a woodpecker comprises three layers; exterior keratin layer (rhamphotheca) composed of overlapping scales, middle foam layer, and inner bony layer composed of mineral and collagen fiber. Indentation testing revealed that the hardness value of the inner layer is two to three times higher than that of the exterior layer. The overall design of the beak, tongue, and hyoid bone with their specific structure-property relationships in addition to the subsystem designed for shock mitigation appears to have been specifically designed for absorbing energy as they effectively dissipate energy as a whole. The perfection of the beak's architectural complexity and fine systemization are highly indicative of it being designed by its Creator.

[7] “But ask the animals, and they will teach you, or the *birds* in the sky, and they will tell you;
[8] or speak to the earth, and it will teach you, or let the fish in the sea inform you.
[9] Which of all these does not know that the hand of the LORD has done this?
[10] In his hand is the life of every creature and the breath of all mankind.
(Job 12:7-10)

INTRODUCTION

Energy absorption is the dissipation of kinetic energy during dynamic loading to protect a body [1]. Undesirable crash such as collision between cars or between football players results in several problems from the slightest bruise or fracture to severe concussion or death. Murray *et al*. [2] reported that the 38 % of head injuries are caused by motor vehicle or sport accidents in Europe and 64 % in the USA. For humans, only 9 g’s (nine times that of gravity force) can cause a head injury, and approximately 100 g’s causes traumatic brain injury [3]. The maximum survivable g-force for a human is approximately 46 g’s though race car drivers have reportedly survived crashes of over 100 g's [4, 5].

In creation, however, we can observe and learn what God has designed to help mitigate impacts and crashes like woodpeckers pecking on trees. Woodpeckers show amazingly efficient shock absorption without any damage to their beaks or brains while pecking. As a woodpecker slams its head at 7 meters per second while pecking against a tree for food, enormous forces up to 1,000 g’s can arise [6-8]. In spite of huge and repeated shocks, no damage to the beak, brain, or head of a woodpecker occurs. Many researchers have studied the morphologic features of woodpeckers that are responsible for withstanding high impacts. These features are as follows:

1. Thick neck muscles [9].
2. Third inner eyelids, which act as a seatbelt and alleviates eyeballs popping out.
3. Thick skull comprised of spongy bone distributed unevenly in the front and back (Fig. 1(a)).
4. Hyoid bone, which raps around the head in a spiral fashion to mitigate shock and serve as a “seatbelt” for the brain [10, 11] (Fig. 1(b)).
5. Subdural space between the skull and brain is very small and does not allow for relative motion [7, 12].
6. No rotational momentum, just linear momentum observed during the strike [8].

These factors have been used for explanation to support the creation and design theory [13]. Adding to the morphological characteristics of woodpeckers, here, we will stress the multiscale hierarchical structure and mechanical properties of the woodpecker beak. With this information we will assess the design of the beaks for pecking trees and will indicate how these function-oriented structure-mechanical property relationships serve as the foundation for further intelligent design studies.

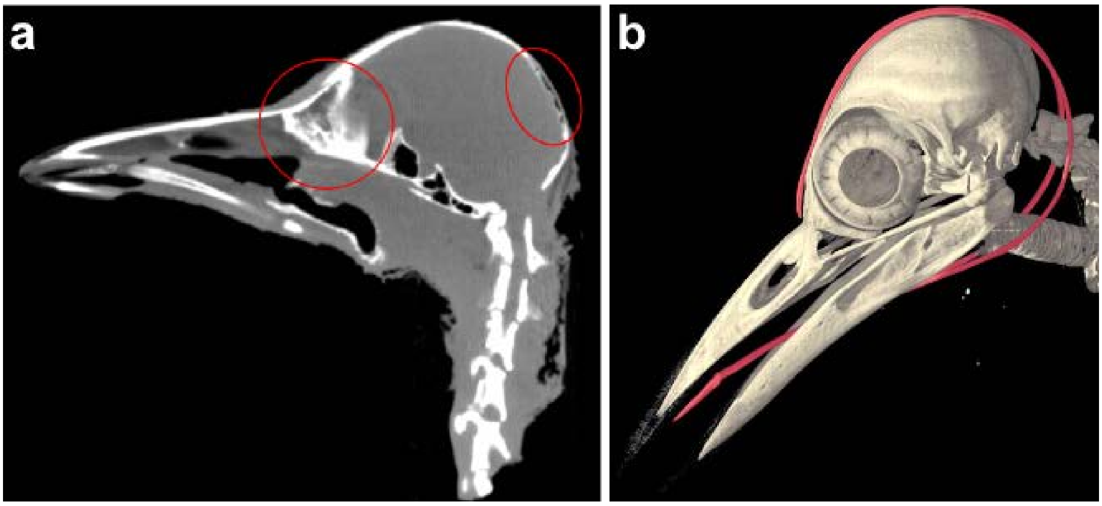

Figure 1. The image taken by micro CT on the woodpecker head shows the thick skull with a spongy bone (indicated by red circle), and (b) hyoid bone connected to the tongue in red illustrating the wrap-around the skull
(*Courtesy: http://digimorph.org/specimens/Melanerpes_aurifrons*.).

METHOD

Fresh Red-bellied Woodpecker (*Melanerpes carolinus)* beaks and chicken beaks were studied in order to quantify the multiscale structure-property relationships using Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and nano/micro indentation tests. The beak samples were fixed in 2.5% glutaraldehyde and post fixed in 2% osmium tetraoxide, then rinsed, dehydrated in a graded ethanol series. Following processing for SEM, samples were prepared using a cryofracture technique to observe the fractured surface, then sputter coated with gold and palladium, SEM micrographs were taken using a JEOL JSM-6500F field emission gun (FEG)-SEM. To prepare samples for TEM, osmium tetraoxide fixed samples were embedded in Spurr's resin, and ultra-thin sections (60-80 nm) were cut on a Reichert-Jung Ultra cut E ultramicrotome, and stained with uranyl acetate and lead citrate. Stained sections were examined by using a JEOL JEM-100CX II TEM at an acceleration voltage of 80 kV.

In preparations for micro/nano indentation tests, the samples were cut in a direction transverse to the long axis of the beak using the diamond saw and mounted in epoxy using a cold mount technique and polished thoroughly. Micro-indentation was carried out on the beaks using a Vickers hardness tester (LECO Corporation, St. Joseph, MI) to examine the microhardness. The tester has a pyramidal diamond tip, and 100 g-force was the applied maximum load. Nano-indentation tests were performed using the Triboindenter® (Hysitron Inc., Minneapolis, MN) with a Berkovich diamond tip. The loading condition was controlled as follows: 20 s loading segment, 40 s unloading segment with 9000 μN applied maximum load.

RESULTS

Structure

Observations of the woodpecker's beak show hierarchical multiscale structures that contribute to the woodpecker's capability of drilling a hole and absorbing energy. At the macroscale level woodpecker beaks are well designed for poking holes in trees and for pecking to communicate to other woodpeckers in a more rapid, but lesser force for making sounds. As a penetrating tool, the angle of the beak tip (and beak) is appropriate. The sharpness of the beak is neither too blunt like a chicken's beak nor too sharp like a hummingbird's beak. The measured angle of the woodpecker's beak was approximately 25~30˚, and the curvature of the woodpecker's beak tip was 19.07 mm^{-1} for the upper beak and 12.01 mm^{-1} for the lower beak (Fig. 2(b)).

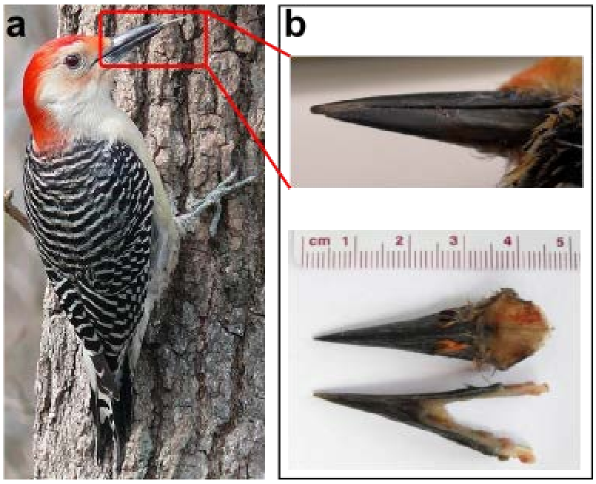

Figure 2. (a) A male Red-bellied Woodpecker and (b) upper and lower beaks of the woodpecker having 25~30˚ angle.

As shown in Figure 3, SEM images revealed that three distinct structural layers form the beak: an exterior rhamphotheca layer, a middle foam layer, and an innermost bony layer. Each layer has a unique material and sub-structure. The rhamphotheca is comprised of keratin scales arranged in an interlocking pattern, and the size of each keratin scale is $55 \times 15 \times 0.2\ \mu m$ as shown in Figure 3b. Figure 3c shows the rough surface of the keratin scales after fracture. The rough surface enhances the frictional force between the scales, so that the impact occurring during pecking can be dissipated by friction. The amount of force required for sliding a solid resting on a flat surface depends on the coefficient of static friction. It is given by following equation:

$$F_{horizontal} = \mu \times M \times a \qquad (1)$$

where μ represents the friction coefficient, M is mass, and a is acceleration applied to a body. The rough surface of the keratin scales increases the friction coefficient, thus the total dissipated force is increased. Figures 3(d) and 3(e) show that the middle foam layer exhibits a porous structure of a closed-cell type of foam at the interface where the exterior layer and the inner layer are joined. The foam layer has the porosity of 27~30% at the location near the rhamphotheca or the bony layer, and 50~65% at the middle of the foam layer. The innermost bony layer, as shown in Figures 3(f) and 3(g), has a microstructure analogous to synthetic long fiber-matrix systems where the fiber is collagen and the matrix is mineral. The microstructure of the bony layer suggests that the core part of the beak is hard and tough like that of bone.

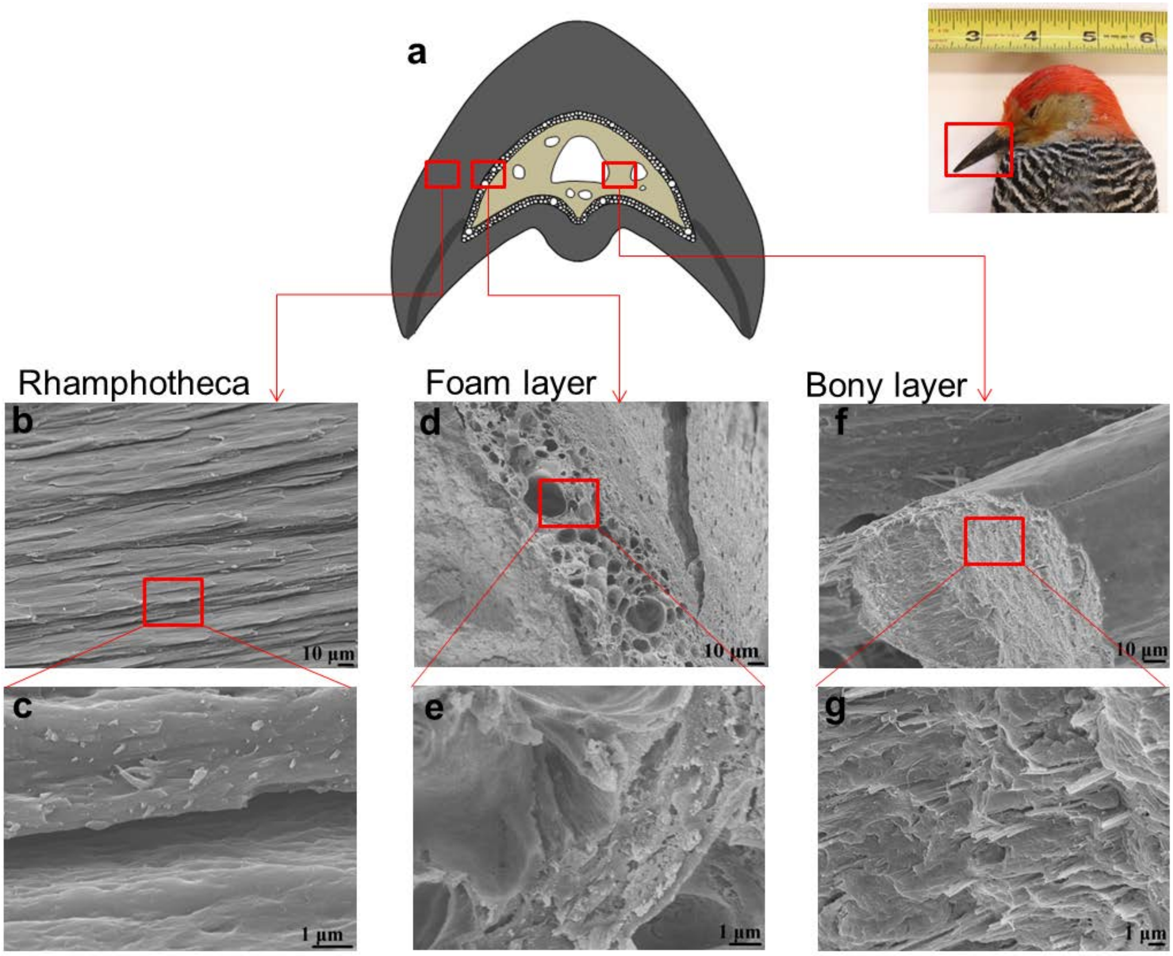

Figure 3. Microstructure of the upper beak of the Red Bellied Woodpecker obtained from Scanning Electron Microscope showing (a) the schematic of the cross-sectional view of the woodpecker upper beak comprising three layers: an exterior keratin layer (labeled a rhamphotheca), a middle foam layer, and an innermost bony layer, (b) the rhamphotheca constituting many scale-like features, (c) a few keratin scales showing the rough surface of the rhamphotheca, (d) the foam layer with a porous structure, (e) the inner structure of foam layer, (f) the innermost bony layer, and (g) the glass-like mineral and collagen fibers shown in the bony layer.

The microstructure of a chicken's beak is observed for comparison to the woodpecker's beak. While the woodpecker's beak is used for penetrating and grabbing food deep within a tree, a chicken's beak is used for grabbing food but not from deep sources like in a tree so the design is different because the function is different. Figure 4(a) shows the SEM images of the chicken's beak having two layers (a rhamphotheca layer and an inner bony-foam layer) while the beaks of woodpecker exhibited three layers (a rhamphotheca, a foam layer, and a bony layer). Humans have not observed how shock waves could create the foam layers found in the woodpecker's beak. Hence, the distinction between the chicken's and woodpecker's beaks could easily be argued as engineering design optimizations. As shown in Figure 4(b), the rhamphotheca of the chicken's beak is also comprised of keratin scales with a dimension of $30\times 10 \times 1$ µm, which are thicker than that of woodpecker's beak. Thinner keratin scales allow the woodpecker's beak to have more frictional surface area, so that the beaks are able to dissipate more energy via friction. The inner layer of the chicken's beak is a bony material similar to the woodpecker's beak although the geometric structure is different. Depending on the amount of a bone's porosity, in general, bone is divided into compact bone and trabecular bone. With 5-30% of porosity being classified as compact bone, and 30-90% of porosity classified as trabecular bone. Figures 4(c) and 4(d) show the two kinds of bone in the bony layer of the chicken's beak. While the trabecular bone of the chicken's beak is a closed-cell type of foam with a membrane, the inner layer of the woodpecker's beak is sturdy, has very little porosity, and has a thicker bony layer.

In the literature, discussions about other birds have been offered when considering their beaks. For example, the beaks of toucans and hornbills are constituted of two layers similar to the chicken's beak studied here. Also, toucans and hornbills will grab food and crunch it with their beaks similar to a chicken in a quasi-static manner. In contrast, the woodpecker's beak is designed for high rate, dynamic events loaded axially. Their beak layers include a rhamphotheca layer made of β-keratin and a foam layer made of mineralized bone [14] similar to the chicken's beak. The rhamphotheca of the toucan and hornbill beaks comprise keratin scales as shown in Appendix 2(a), illustrating that the shape of a keratin scale for a toucan's beak is more rounded compared to a woodpecker's beak or chicken's beak. The shape of a toucan keratin scale results in anisotropy for the rhamphotheca, meaning that the toughness is more directionally oriented for crunching. Also the shape of the inner layer of a toucan's beak is a foam structure as shown in Appendix 2(b). Hence, these microstructural differences illustrate the engineering specificity of design for their particular function within environments in order to obtain food.

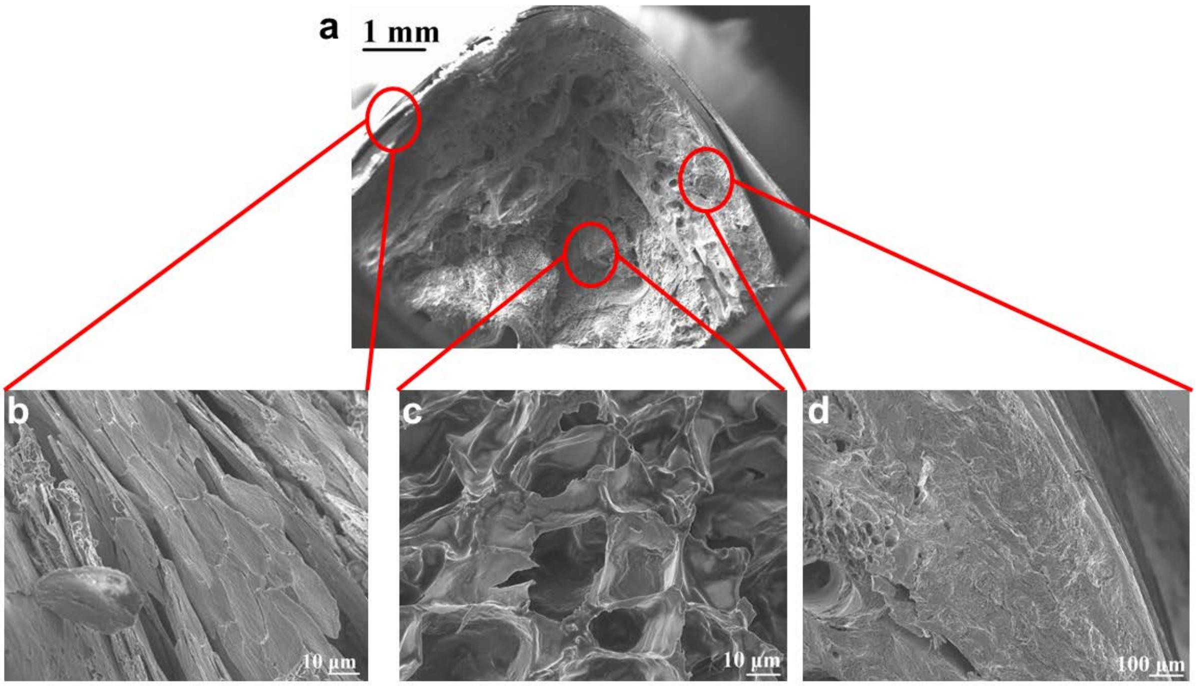

Figure 4. Microstructure of the upper beak of the chicken garnered from Scanning Electron Microscopy shows (a) a cross-section view of the entire fractured area, (b) an exterior rhamphotheca layer comprised of β-keratin scales, (c) an inner foam, and (d) an interior bony layer.

Figure 5 shows TEM images illustrating the nanostructure of the rhamphotheca at the very tip of the woodpecker's beak and chicken's beak. The keratin scales shown in Figure 5 are essentially equiaxed, but the diameter of the woodpecker keratin scale is 10-15 μm and the chicken keratin scale is 20-30 μm. The smaller scale size for the woodpecker indicates that the wavy sutures that connect the scales have more boundary length. There is a very small gap within the suture lines and this admits friction. As such, the woodpecker's beak would admit more frictional dissipation than the chicken's beak because of the larger ratio of interscale contact area over which frictional force may be applied. This signifies another design difference between the chicken's beak and woodpecker's beak in consideration of their functions.

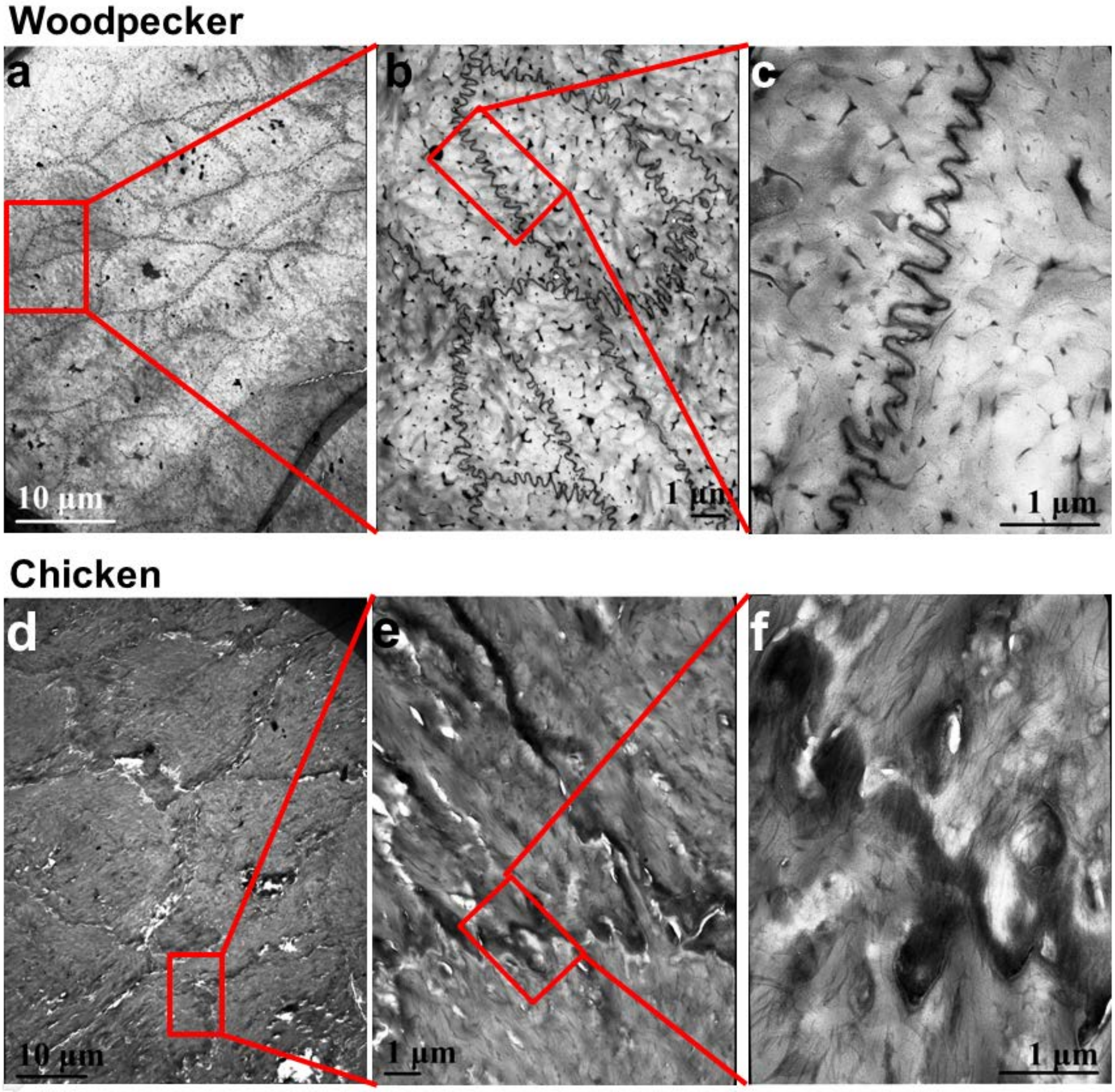

Figure 5. Transmission Electron Microscope images of the woodpecker's and chicken's rhamphotheca from the very tip of the beaks in a cross-sectional view: (a) keratin cells of the woodpecker; (b) regular wavy lines of the keratin cell boundary; (c) wavy boundary and fibers; (d) keratin cells of the chicken beak; (e) irregular wavy lines of the keratin cell boundary; (f) boundary and fibers.

Mechanical Properties

Mechanical properties of the woodpecker beaks were examined using microhardness tests and nanoindentation tests. Since the surface roughness influences indentation testing, we polished the sample surfaces thoroughly before performing the tests. The mean value of microhardness for the rhamphotheca and bony layer is 323.63 ± 8.77 MPa, and 635.82 ± 40.87, respectively. The mean values of nanohardness for the rhamphotheca and bony layer is 470.23 ± 68.89 and 1219.64± 298.54, respectively (Table 1). The result of indentation test implies three things. First, the bony layer is two to three times harder than rhamphotheca, so the inside of the woodpecker beak is harder than the outside of the beak. The soft and ductile outer keratin of the woodpecker's beak, protects the beaks from fracture due to impact. Second, the hardness (associated with the strength, modulus, and stiffness) is almost two times higher at the nanoscale than at the microscale. This is because micropores lower the overall global hardness but not at the nanoscale. Third, the standard deviation shows that the bony layer is heterogeneous material, and the rhamphotheca is homogeneous material. From the microstructure of the bony layer, we can observe that the bony layer is mainly composed of two different materials, which are collagen fibers embedded within a mineral matrix.

Table 1. The hardness values from micro-indentation and nano-indentation. The bony layer is two to three times harder than that of the rhamphotheca.

	Rhamphotheca (exterior layer)	Foam layer (Middle layer)	Bony layer (interior layer)
Microhardness (MPa)	323.63 ± 8.77	N/A	635.82 ± 68.89
Nanohardness (MPa)	395.51 ± 78.24	243.05 ± 137.78	1155.37 ± 187.89

Interestingly, one of the microstructural differences between the various bird beaks is the beak core. The woodpecker's cross section is actually very similar to the ram's horn (cite paper). A ram's horn, which is also subjected to an extreme loading, has similar structural components like that of the woodpecker's beak. The ram's horn is composed of an exterior keratin layer and an interior bone layer [15]. No matter what classes they belong to, for example mammal or avian, there exists the same design strategy for their material/structure for dissipating the kinetic energy and keeping the system intact. Keratin, a viscoelastic material, has a multifunctional role such as being waterproof, assist in decelerating impact speeds, and protecting the inner parts. The bony part located inside supports the body from the exterior impact. Finite element simulations further confirmed that a keratin beak has a role in dissipating the impact energy [17].

By the process of random mutation and natural selection, it is hard to explain the fact that the unique structure of the bony layer exists in the woodpecker's beak, not other kinds of birds, and is similar to that in the ram's horn. If one were to assume that the woodpecker and chicken were closer to each other in the evolutionary tree than the woodpecker and ram, then one would expect that all of their structures would be more similar. However, the woodpecker and ram are not close species and have very dissimilar body parts, but woodpecker's beak and ram's horn share similar function and utilize similar engineering design for dissipating shock waves.

Flexural stiffness

The flexural stiffness of the woodpecker beak is analyzed to investigate the resistance to the bending stress. The flexural stiffness is a combined measure calculated from 'E×I,' where E is the Young's modulus (material property of the beak), and I is the area moment of inertia (geometric distribution).

The cross-section changed like a shape of $\nabla \rightarrow V \rightarrow U \rightarrow C$ with respect to the location on the beak tip to the beak root as shown in Fig. 6(a). The area moment of inertia (I) changed from 0.02 - 6.96 - 42.04 - 21.65 mm^4 from the beak tip to the beak root of the lower beak. The modulus (E) obtained from compression tests at each location changed 2.10 – 3.68 – 7.92 GPa from the beak middle section to the beak root. Since the very tip of the beak is a cone shape, it was excluded from compression testing. The changing stiffness comes from the changing area fraction of each material through the cross section along the beak as shown in Fig. 6(a) and the overall geometry change. The area fraction for each layer over the cross-sectional area was analyzed using the Image J software (National Institutes of Health, Bethesda) and is depicted in Fig. 6(b). The portion of the bony layer (hard part) increased while the portion of the rhamphotheca (soft part) decreased from the beak tip to the beak root. The flexural stiffness (EI) increased 14.61 – 154.71 – 171.43 GPa-mm^4 from the beak middle section to the beak root (Table 2). The tip part of the beak is relatively flexible to bend, and the root part is rigid by comparison and is similar to the ram's horn design. This changing stiffness was also observed in insect wings in order to resist aerodynamic bending: the greater Young's modulus and flexural stiffness were found to be closer to the root of the wings [18]. In addition, the changing Young's modulus will change the speed of the elastic wave generated from impact, forcing the wave into the hyoid bone, which dissipates the energy.

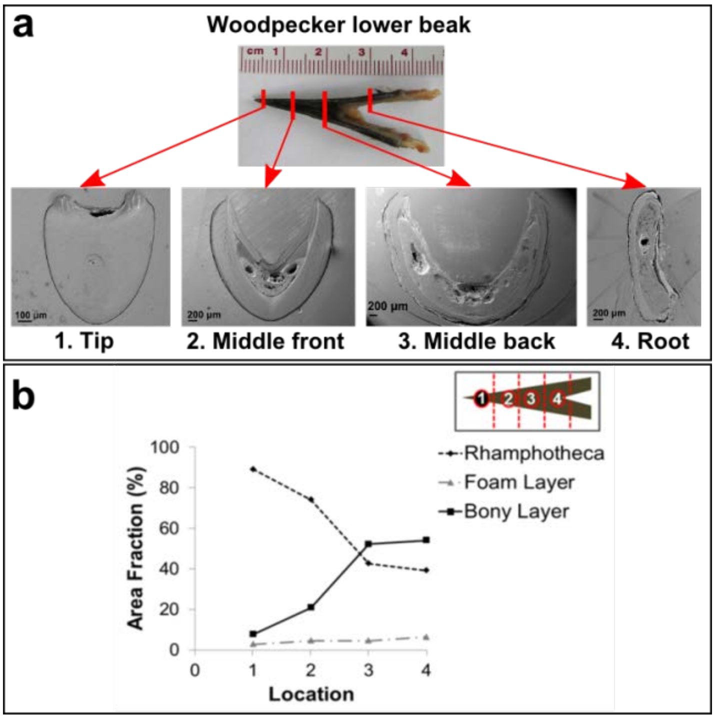

Figure 6. The cross-sectional shape (a) and the area fraction (b) of the woodpecker beak are changed along the beak from the tip to the root.

Table 2. The area fraction, area moment of inertia, and the flexural stiffness of the lower beak of the woodpecker are changed along the beak from the tip to the root.

Distance from the tip	Cross-section shape	Area (mm^2)	Rhamphotheca		Foam layer		Bonny layer		Modulus (Compression) (GPa)	I (mm^4)	Flexural Stiffness (GPa-mm^4)
			Area fraction (%)	Area (mm^2)	Area fraction (%)	Area (mm^2)	Area fraction (%)	Area (mm^2)			
1	∇	0.47	90	0.42	2	0.01	8	0.04	-	0.02	-
2	V	12.39	75	9.29	3	0.37	22	2.73	2.10	6.96	14.61
3	U	27.14	42	11.40	4	1.09	54	14.66	3.68	42.04	154.71
4	I	24.50	37	9.07	5	1.23	58	14.21	7.92	21.65	171.43

DISCUSSION

The function oriented structure

Birds' beaks have a crucial role for maintaining life of birds. For birds, beaks function like rodents, teeth, and hand used for pecking food or trees, crushing seed, or grabbing something. According to their forage type or lifestyle, the force acting on the beak would be different from species to species; however, no matter how much force is applied, a bird's beak needs to dissipate dynamic impacts. If not, birds could not sustain their life. As shown earlier, the complexity of different birds' beaks are well-organized to absorb the impact generated in the particular environment in which they live.

Principles of engineering design applied to structure-property relationships initiated by the Creator can be adapted to man-made devices with a great success. Creation scientists and secular scientists pay attention to the relationship between naturally occurring multiscale structures and their associated complex functions. Chinese scientists, Xia and Jiang [19], said, "the creation of such complex functionalities in bio-inspired materials depends on well-ordered multiscale structures. Here, we present a strategy for the design of bio-inspired, smart, multiscale, interfacial (BSMI) materials based on this concept." This example along with others in the literature argue for only natural evolutionary causes, yet provide no mechanisms for the creation of their structure-property relations given the particular living environment. The mathematical use of random functions has not been shown to create such complex function-oriented hierarchical structures; on the other hand, design engineers have employed such concepts in nature and have applied them to various armor systems for example. This argues for an intelligent designer outside of the engineered system.

Engineering design optimization

Regarding the concept of the engineering optimization, the woodpecker's beak is a very complex apparatus. Design optimization is 'a systematic process by which a measure of objective function (e.g., weight, cost, strength, and deflection) is optimized (minimized or maximized) by varying the design variables while satisfying all the design constraints (i.e., requirements and limitations)' [20]. The more objectives, the more complicated it is to find an optimized solution. If there are two objective conditions, for example, the beak being able to penetrate wood and grab worms for food, then there are multiple design solutions that satisfy the two objectives. When there are at least two objectives, it is impossible to find the exact answer; thus one must try to find the optimized answer, which is called "Pareto Optimum."

A woodpecker’s beak has several objectives such as shock absorption to protect head and body, be lightweight for control, have sufficient strength to penetrate into wood, have an internal damping to reduce the vibrations generated from pecking trees, and a fairly large bending strength. With this many objectives, the complexity increases. In addition to the many objectives, there are constraints including only biomaterials. Although the addition of constraints reduces the solution space, more complexity is induced. When this much complexity is involved, natural processes have not been observed to have the creative power to afford a solution. The multiple solution space requires an intelligence outside of the system to pick the appropriate solution. This is the typical engineering design process. For solving this particular complex problem related to a woodpecker’s beak, the Creator chose a multi-layered hierarchical structure in which an inner bonny layer provides enough strength to make a tree hole and resist the bending stress, but still have the rhamphotheca made of β-keratin be a viscoelastic material to induce damping of vibrations. The middle foam layer is used to attach two of these dissimilar materials in a graded form providing flexibility at the contact region where it is important due to high stress and contact failure.

God as an engineering designer

By this structure-property study of a woodpecker’s beak, one can assert that the complexity is great requiring a creator to design it. Then, how can we know that the one who designed the woodpecker is the God of the bible? Are there other evidences of God giving directions for specific engineering designs where the main concern was a structural member? In a word, yes!

> “Build an altar of acacia wood, three cubits high; it is to be square, five cubits long and five cubits wide… Make the altar hollow, out of boards. It is to be made just as you were shown on the mountain” (Exodus 27:1, 8)

God gave very specific dimensions and geometry (square) for an altar that was supposed to structurally support some other entities. God did not give a command to make the altar in the above example with an approximate size but gave specific numbers.

> “Make yourself an ark of gopher wood. Make rooms in the ark, and cover it inside and out with pitch. This is how you are to make it: the length of the ark 300 cubits, its breadth 50 cubits, and its height 30 cubits. Make a roof for the ark, and finish it to a cubit above, and set the door of the ark in its side. Make it with lower, second, and third decks.” (Genesis 6:14-16)

In the above mentioned scripture, God commanded Noah to build a huge structure (ark) to house many animals, his family, and himself. According to God’s instruction, the dimensions of the Ark were to be 300 cubits long, 50 cubits wide, and 30 cubits high. Not only did God give the structural dimensions, He also discussed several hierarchical features. The ark was to have three decks, and each of the decks was to include many rooms. God specified gopher wood for the material to build the ark, and pitch was called out for waterproofing. God did not say “choose any hard woods,” or “make the ark to have enough space to load every kind of animal.” God gave very specific details of the ark before construction, which engineers call a “blueprint.”

The ark that God designed was proven to have structural dynamic stability to resist wild waves [21, 22]. The natural frequency, which is one factor to examine the stability of structures, is related to length, modulus, area moment of inertia, and cross sectional area of a structure. God considered all of these mechanical factors to design a safe ark. Likewise, the flexural stiffness of a woodpecker's beak that gradually changes from the tip to the root also was very well designed to resist high impact. Since the concept of the moment distribution was introduced in early 1930's [23], it has been less than 100 years that people have been concerned about flexural stiffness and its effect on the structure. From the beginning of the creation, however, God created the fundamental principles of material and structure. The examples shown in the aforementioned bible verses reflects the specificity required in the engineering design process. The result of the engineering design process was not only reflected in the altar and ark but also exhibited in woodpecker's beaks as well.

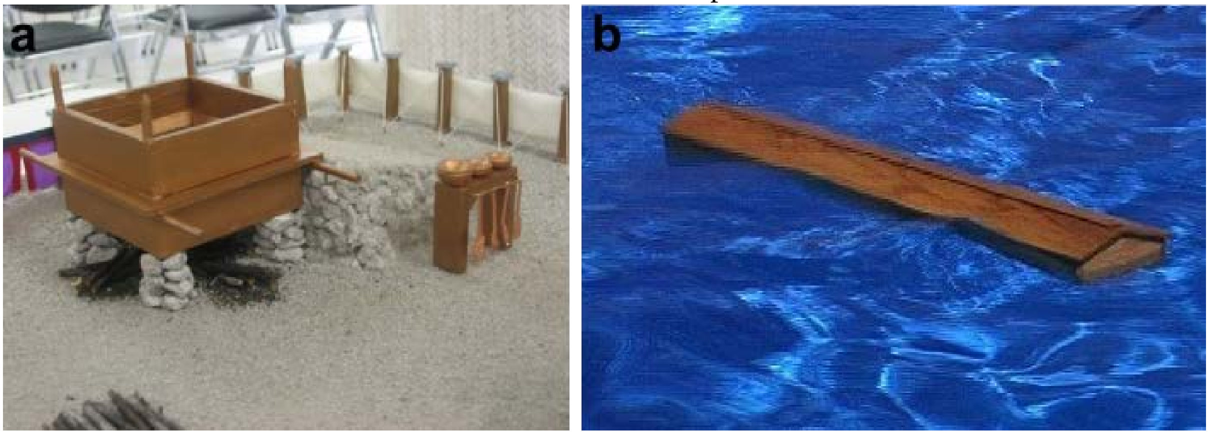

Figure 7. The examples of structures that God gave specific and detail blueprint. (a) altar, and (b) Noah's Ark.

CONCLUSIONS

Woodpeckers have elaborately designed beaks that allow pecking trees at 6-7 m/s without any damage to their beaks or brains. At the microscale, the woodpecker's beak comprises three layers: rhamphotheca, foam, and bony layer (compact bone type). In comparison, the chicken's beak comprises two layers: rhamphotheca, and boney layer (trabecular bone type). At the nanoscale, a wavy structure, which plays a role in dissipating the shock wave, was exhibited in the woodpecker's rhamphotheca but not in the chicken's beak. The micro/nano hardness of each layer of the woodpecker's beak was examined showing that the interior layer is two to three times harder than the exterior layer. Also, the flexural stiffness of the woodpecker's beak changed along the beak length, where the root was rigid but the tip end was able to deflect. The complexity in the function and structure of the woodpecker beak implies that they have been designed by intelligence outside of themselves. We assert that it was the God of the bible!

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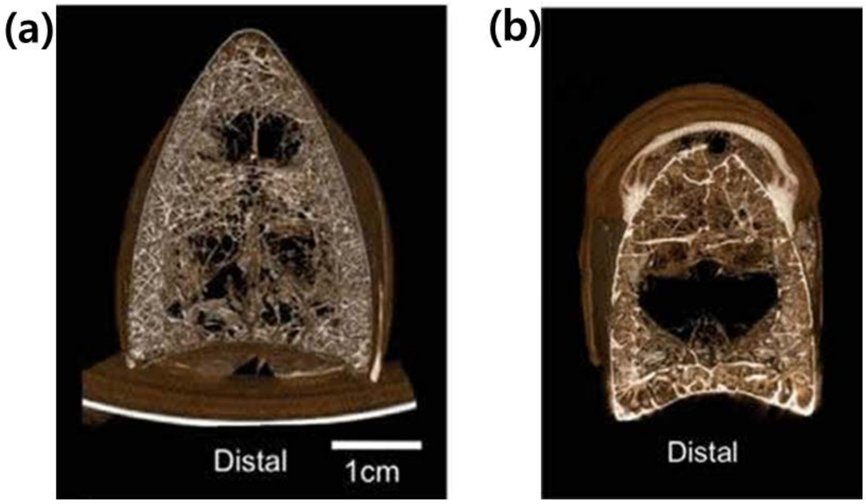
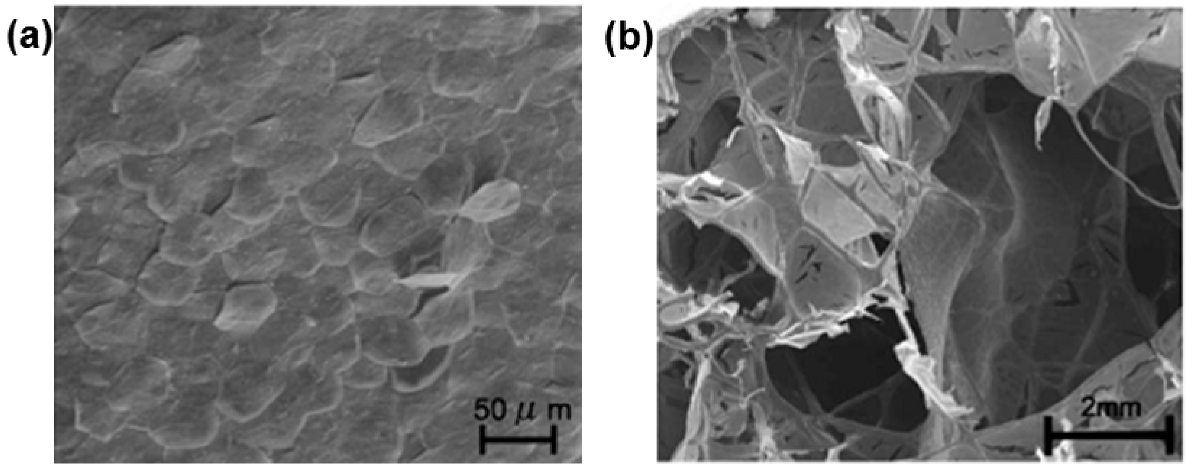
APPENDIX



Appendix 1. *(Courtesy: Toucan and hornbill beaks: A comparative study)* The computed tomography of (a) a toucan beak and (b) a hornbill beak.



Appendix 2. *(courtesy: The toucan beak: Structure and mechanical response)* Scanning electron micrographs of the (a) rhamphotheca of a toucan beak (keratin) and (b) bony layer of a toucan beak (foam).