CHAPTER 2

Sponges versus foams: Nature and human artefact *

Axel Thallemer [Hong Kong University of Science and Technology]

Abstract: Natural sponges have been used as tools by humans, and even by animals, since ancient times. Design has evolved as purpose-driven form, going from hand axe to computer mouse and beyond, by improving tools for the better progress of humankind. Industrial design – as distinct from styling – can be based on research in the natural sciences. Looking at paragons in nature (in the present case, marine soft sponges) can lead by heuristics and by analogy to new microstructures, and, with the help of additive-generative fabrication, can lead to the creation of new hard or soft "metamaterials".

Innovation today most likely starts from the specific designing of "new" [instead of existing] materials, designed to fit with their prospective application, while taking their respective manufacturing technologies, and ecological and economical contexts, into account. This can yield lightweight structures for conserving resources and energy in aerospace and mobility applications, or scaffolds for biomedical purposes. Representational heuristics exemplify the ideation of new lattice structures from natural sponges from the Caribbean, the Mediterranean and the Philippines to artificial soft and hard foams. Semi-finished products are juxtaposed to functional components with differentiated internal structures. The latter exhibit a microstructural architecture through interdependence of structure and processing, as well as resulting properties and performance. This presentation offers a visual exploration of purposefully designed materials versus solid matter.

I should begin with an acknowledgement that what I am about to present is funded by the Republic of Singapore, by the Ministry of Education, and their Academic Research Fund [Start-Up Grant R-298-000-008-133]. It is the conclusion of a three-and-a-half year research project which is about to conclude (August 2018).

Inner structures

Humans have always made tools, for hundreds of thousands of years. How many years is a subject of dispute, because the longer the science goes on, the more the dates tend to change, and generally they tend to be older and older. It is always a question of the human hand, and the interface with the environment through mobility (also called mobiligence, meaning the interaction of the brain, the arm and the hand, via the eyes, with our physical environment). And this leads us directly to marine sponges. By now they are already some 300 million years old – others say more – and finally, after about 200 years of dispute, the scientists have decided that these are the oldest animals on earth.

[By the way, we heard earlier about dolphins, and their use of sponges as tools. I might add a bit of a gender perspective here. According to the research paper in question, it is only female dolphins that use sponges as tools, because the males are hunting in groups, and when the females are having babies they cannot participate in these hunting groups. So they are alone, and in order to forage the seabed they pick up and use sponges as tools. However, when there are no young to be taken care of, they join the male groups for hunting.]

Here we have an image from the eighteenth century – early plastic surgery. The image portrays reconstructive upper lip nose tissue being taken from the patient, and put onto a small slice of sponge, which was then sewn into the mouth of the patients, and the cells were grown there. So you see, two hundred years ago the physicians already knew about sponges and their genetic vicinity, in connecting tissue, to human DNA.

Also, from Robert Hooke, a seventeenth-century sketch of a sponge – and this is exactly what interests me most – namely the bifurcation of the primary and secondary fibres. This is precisely what I have been looking at. And in addition, these are the soft sponges – some say 5,000 or 6,000, others say several thousands more (for sure they are not all known yet… the numbers will grow as science progresses). But only up to 8 are entirely soft, as known to date. This definition – "entirely soft" – means no spicules whatsoever. No calcium carbonate spicules, no silicium oxide spicules. Just pure soft matter, being supported by anastomosing fibres. In this particular case, it is also funny when you look at things in linguistic terms – in science it's called Spongin, which doesn't help you that it comes from sponge, because there are different varieties of collagen in the case of sea water sponges and chitin of fresh water sponges.

So we are now moving in closer and closer, and here you see the bifurcation. Then we looked at the elephant-ear sponge, going deeper and deeper into its structure, and at the National University of Singapore, at the Biological Engineering Lab, there was also Raman spectroscopy done on our sponges, to see what kind of chemical elements are in their make-up. And it is very interesting that you find many more elements than what is currently described in the literature. Not entirely surprising, because soft sponges are still widely unresearched, in comparison to the rigid ones.

I find the smaller sponges more interesting, because they tend to be far softer. Also their intricate web is much denser, and more regularly irregularly (you hear it correctly) arrayed, and that is actually the trick in creating new materials for meta-materials, namely that you design them differently. In the past, let us say in the Stone Age, you had a massive rock of stone that you chipped away with a hand axe. But nowadays it is imaginable, just like with sponges, that you design an outer skin, and an inner skin, and that you have an in-between lattice. Of course, we also examined the loofah. I should say that by no means can the loofah be compared to a sponge, because the morphology and the latticework are completely different from an anastomosing sponge.

Now, let us go back in time. This is an image from the Natural History Museum in Washington DC. A petrified glass sponge. You see that not much has changed to nowadays – unfortunately, in most cases, all over the world, in our museums the sponge exhibits are tucked away in corners, and are poorly lit and not displayed with pride. Perhaps that is something that might be changed in the future. These days they are there more or less because otherwise the collection would not be complete, in the sense of a permanent, comprehensive display. But in most cases they are not afforded a dominant view.

Now, in this image we have the famous *Spongia officinalis*, the really soft one. You see already that it is small. And here is an image of another rigid glass sponge. For more than a hundred years, when engineers build high-rise primary structures, they build just like that. You have the vertical beams, you have the horizontal girders, and you have the diagonal bracings. And this has been true in nature for hundreds of millions of years for a very particular reason – you have to withstand gravity, and you can only do that when you have longitudinal forces led directly to the foundations, and then you need the horizontal bracing so that the whole thing does not collapse, and then again to deal with the shearing and the wind forces (and, in the case of sponges, water forces), you need the diagonal stiffeners.

And this was already known about 150 years ago; when you look at these posters – from the Paleontological Museum in Munich, my home town – there too a lot of sponge research has been conducted over the past 200 years. And the interesting thing is that the sponges are quite well preserved, even when they are petrified. When you see how delicate they are, on the one hand, and on the other hand when you look at their metamorphoses into stone, they are easily recognisable. The only thing that I ask myself is – where are there entirely soft sponges in petrified form? No one has been able to answer that for me, and there are also no examples – at least not yet… Maybe one day researchers will find a way to identify the remnants of soft sponges from after a couple of hundred million years ago, and in what ways they might be detected. That is the problem, because with the rigid ones you are looking at here, it is quite easy. The geological metamorphoses survived.

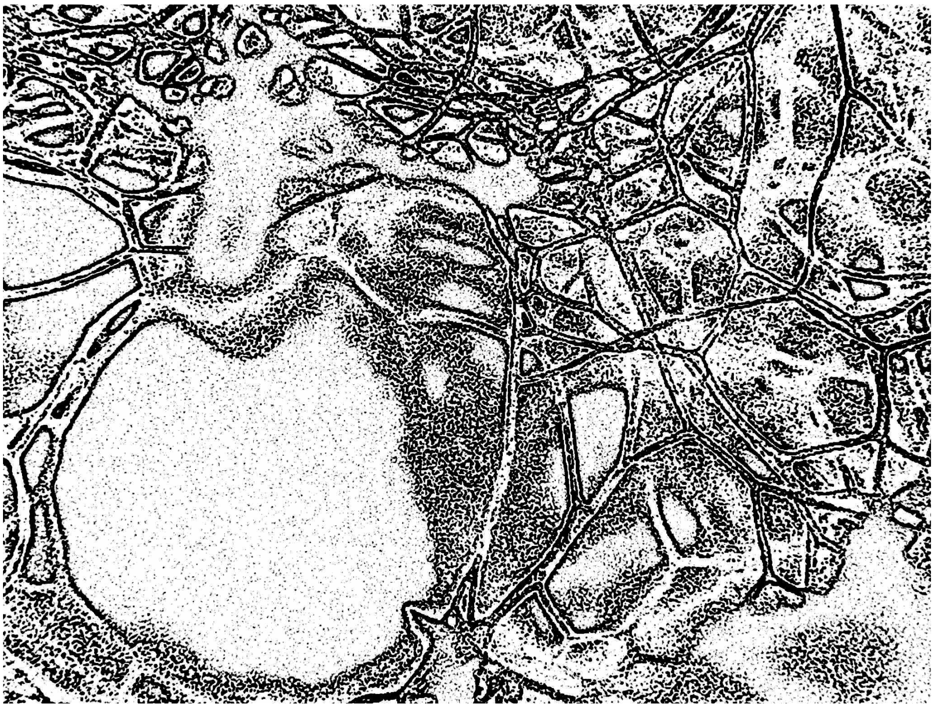

Figure 1: Micro-structure of a natural soft sponge

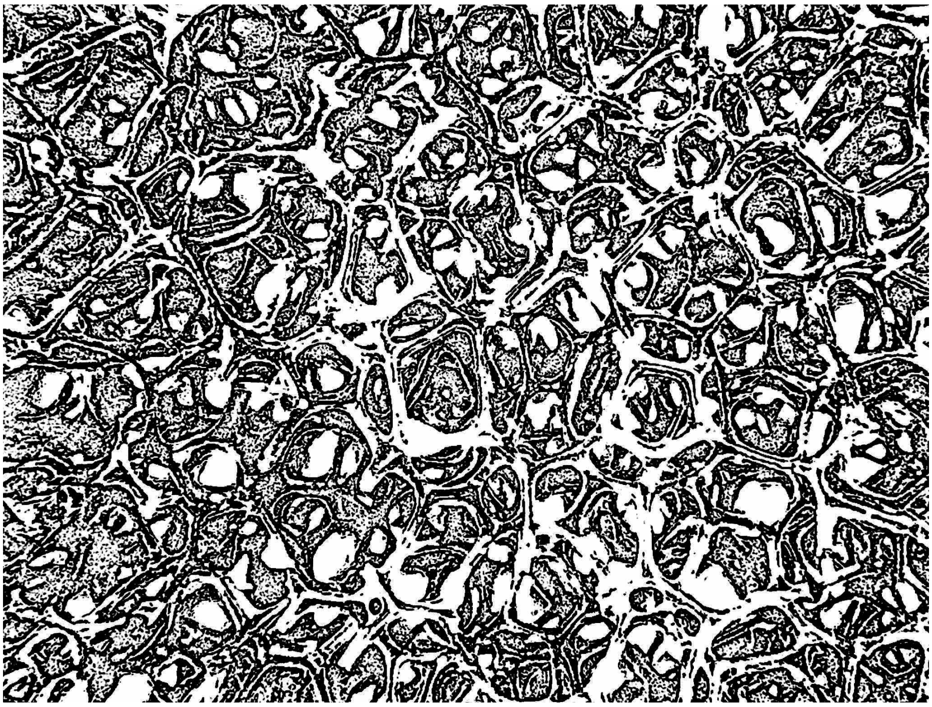

Figure 2: Micro-structure of a manufactured synthetic sponge

In Baden Württemberg there are fossilised reefs of sponges that are 200 to 300 metres high. Here you see a single one. These big white formations are petrified sponges. Here you see the [Hohler Fels] Hollow Rock Cave, and the small ivory carving found there is about 40,000 years old. A human piece of sculpture for the palm. It is from this very area where the sponges are petrified. You see, not only corals make reefs; sponges can also make reefs. And there are underground mines where the petrified sponges are taken out of the earth and then ground into ultra pure powder for medical uses.

Let us look now at artificial sponges. [*See figures 1 and 2 above*] At a certain point in time, humans wanted to have artificial sponges. Take a look here. We are not going through the scientific definition, with the pores and the more regular pattern, or you have more or less spheres attached to it… This is a metal foam, and this is anastomosing, so in this case it is referred to as metal sponge, because it looks very similar to sponge. And here you see a variety of different industrial components – this one particularly is interesting because it has this internal structure. With that one, what you are seeing is like honeycomb. Actually, this is boring stuff. It is widely known in engineering. What is *not* known and researched is this image here. How is the sponge material behaving? And the interesting thing is the application. This is what I am currently working on, as a derivation from my sponge research in the medical area.

Improving bone plate implants

So, the first thing that I am doing, right now in these days, is the improvement of bone plates. For instance when a thigh bone is broken and you need to tighten it. The advantage that we obtain from the sponge research that we have conducted is that we are able to design – out of stainless steel, or titanium alloy – a bone plate which has the stiffness of a natural bone, despite the fact that it is metal, and the strength of metal. That's the problem – because if you just put in a stainless steel or titanium plate, then notch stress is exerted onto the thigh bone, and it is most likely to break right before or after that implant. Therefore it makes a lot of sense to have a plate on the thighbone which is behaving structurally, in terms of elasticity and the strength, as closely as possible like natural bone. But it must be of metal for the tensile forces as it must be as small as possible. Because where the bone plate touches, the bone tissue dies. So you have to keep the contact area as small as possible. And you have to do what is being called "osseo-integration", which means that the cells of the bone should have the possibility of fast growth into the material, and should like it there. This is functional morphology being inserted. You can all learn that from sponges. In many cases, in the past, the choice of materials was dictated by whether they were particular solid elements or alloys or composites. But here, in this new situation, the geometry is more important than the solid material that you are choosing.

After the bones plates, the next thing that we are preparing, from this year onwards, is to make improvements in the current knee implants. You should know that currently there are only three sizes – small, medium and large – for the whole of humankind, which is quite ridiculous. And the same goes for hips, and the same for shoulders. Most people don't know this. They look at you and say "Oh… small… medium… large…" But definitely you will never again move like you used to. So here the dream – but this is at least five to ten years away – is to make patient-specific implants. And again, where do sponges come into this? The normal knee implant is just a cast, wrought or milled piece – when you have less money, it's made of stainless steel; when you have more money it's made of titanium alloy. But now the back side could be additively manufactured with a lattice derived from sponges, and that potentially gives you better osseo-integration. In other words, the bone cells quickly grow into the material, and it is like a natural glue or cement, so to speak.

We have here a South-East-Asian newspaper clipping in Chinese from the first quarter of 2018. In fast developing countries they are a bit more adventurous. There the patients do not wait until the Federal Drug Administration has approved it. No, they themselves pay privately, and they say "Just do it!" (Which – if I may say so – is utterly dangerous and irresponsible.) And the surgeons are telling me that most probably the implants will not last longer than half a year, and they tell me that you can only do a knee twice. You have to take it away from the area above the artificial joint. And the implantation of an artificial knee joint is pure handwork and experience.

In countries with less developed health care, some people also have quite severe lower jaw defects. What you see here are complete implants, replacing the natural one. All could be better engineered – which is why I am showing you this. It is an engineering pattern, it is not a sponge-related lattice. Therefore it is not going to work that well. And here we have a lady who was hit by a car in 2017. I happened to visit the company which printed that. With computer tomography they printed her pelvic bone in nylon [polyamide]. And then they made her artificial hip joint fitting from titanium alloy. When I showed this to the surgeons in the National Hospital at Singapore, they gave it less than three months. I won't go into the structural details, but it will not work in the long run. As a human you may weigh in at 50-60 kilos. When you get a couple of G-forces from jumping or falling from stairs, you have several times that weight to fracture. So there are very many dreams currently happening…

Structural metamaterials in engineering

What is more interesting, and quicker in application, is to apply the lattice principle in aerospace – for instance, in seating units for aircraft, with lattices that are differentiated. But again, in these examples that I am showing you, none of these yet have the sponge lattice. So I know that we are at the forefront of innovation here. In this illustration you see a hinge for a car… and these are brake calipers… nice topology… so we are moving away from solid matter to differentiated structures that you see in these parts for cars… wheel suspension… etc. But still none of this is yet spongelike. Here you have joints for car bodies, and there you have bulkheads in passenger aircraft, for the flight attendants' jump seats, all 3D printed, and in this case of aluminium alloys.

These are fasteners for aircraft, and other parts and components, and none of them yet have the sponge lattice. Therefore I know that with this kind of lattice derivations you can, to a certain extent, revolutionise the world, with new printing methods in plastic, of a wing, with internal structure. There are two different strategies: either stress-based isostatic line optimisation or density-based optimisation – again, not sponge. Weight distribution and weight savings, not from the material but from the lattice structure. What I have given you here is an overview of what has happened in the world in the last two years. This is a space frame in a former VW Golf, and this is a reinforcement. And here we have wheels for a car, with an internal structure, and as an industrial designer I can tell you that this was done by an engineer, because of the straight struts, and I can tell you that straight struts don't work perfectly. You can see it here – because straight struts do one thing… they work perfectly in a mathematical way… but when they have reached their limits they fail instantaneously, as in this example… they just crack…

When you look at sponges, sponges never have straight struts, and we know why – because they would break. And instead of having solid pieces, again as I told you, the trend in meta-materials recently is to have skins with internal lattice. Here you can see derivatives for skate boards… bicycles… so it is not only a visual trend that is coming, but also an engineering trend. These are pedals for Formula One racing cars. Of course it is skinned, but in the real application it is sandwiched, so it is printed in one piece, and the internal structure would be non-visible. Here you can see it again… engineering work… all straight struts. And you see this particular pattern which has been known from a Russian mathematician [Voronoi] for over 100 years. And by the way, if you are interested, this is the same algorhythm as the *Euplectella aspergillum* sponge top cover, also known as the Venus Flower Basket. It has the same distribution in the top cover as this mathematical algorhythm. Accordingly it is called the Voronoi pattern. It is pure mathematics. One to one, we find the same in nature. Of course it is only a matter of time before the manufacturers take this on. This is about two months old now. Conventionally fabricated implants are about ten times less expensive than 3D printed ones, but I can tell you that the 3D printed ones are much less reliable to date. So you pay ten times more, and you carry a higher risk of failure. The same with the sports shoes. They are, for the time being, more expensive, and in addition, due to the way they were generated, for sure they don't last that long. So you always end up with less, not more.

Here we have a boxing helmet that my PhD student made. It was tested in the biomedical lab. It is much better than any existing sports helmet for combat sports. And the idea for this was developed from the sponge lattice. And here we have a design from a lady who did her final thesis on helmets for children with special needs [epilepsy]. That safety helmet is intended for home usage.

Why sponges?

Here we have applications in the area of transportation, by which we mean predominantly cars. And this is from a crystal-structure derived lattice, which is also not so good, because of straight struts. Here you see a suspension for a fire extinguisher in an airplane. And here are engineering lightweight structures without bionic influences. So I'm not going into details. As we started here with a hand axe, my student, who is just finishing his graduation thesis, re-did the theme of an axe – these are early trials made of titanium alloy. Here you see the almost finalised axe. It has Y-shaped bifurcations in the handle area, and by vacuum-brazing HSS steel plate in the front and titanium alloy for the handle and the rear. And here you see the 3D printed piece, with skin, in real scale. It is very lightweight as well as being very nice and functional.

How did I come to sponges? I usually design robotic arms and grippers, and therefore I looked at birds' beaks and cartilage and collagen. So this was the one thing that caught my attention. And then the fact that animals apart from humans all grip the same way. And there is a mechanism behind this, which Professor Reuleaux in the nineteenth century already found out. And some 140 years later we transferred this mechanism into these robotic grippers. So this was the preliminary work. I just wanted to show you how I came up with sponges, because they were definitely not on my pathway. The one thing is the bifurcation in trees, where a curvature continuous transition of the splines make a better bifurcation and drastically reduce notch stress – you see this tree and this gripper. And here – it was in Berlin, anatomist Dr. Wolff in 1896, who found out about the cancellous bone structures, where, just like with Gaudi's architecture, you have in these arches compression and tension separated, this was transferred here to this centrepiece of the robotic gripper. And the third gripper here has the mathematical lightweight lattice which are circles or arcs. And then you come to morphogenesis.

When you look at sponges or humans, then you have to look at evolution. And never ever think that evolution stops. When you think of the five fingers of our hands as normal, they were derived from the fin rays of the primordial fish we were stemming from, and then going onto land… transforming flippers to legs and subsequently arms and you never know if in the future we won't have six-finger hands. This is imaginable. [Shows image] Functional. And this is not faked or photoshopped. Nature is constantly trying new things. And even if all humans, like the solid line here, look alike now, you never know if one of these [dotted line] mutations is going to take over… Just like with Darwin's finches, it is an adaptation to the environment. Unfortunately evolution is not foresighted. It is only reactive. So the ones who have the wrong tools (and the wrong hands) are just out of the game… because the survival of the fittest does not mean the strongest, but the most adapted to the ecological niche. Therefore I foresee also changes in our physical appearance for the far future. I don't know what those changes will be, but I just wanted to let you know that five fingers are not a given thing for ever.

There are also designers who make art with that, like this sixth finger worn as a ring, cast in silicon, quite nice…

Morphodynamics

But let us return to the tree. The next thing to consider is morphodynamics. This is very important when you look at the lattices of sponges. In order to understand how they anastomose and grow, you need also to look at trees and morphodynamics. Trees are also sessile. Sponges do not move, although some sponges, when they are babies, have a mobile phase, and they can spin at a very high rate, and even propel themselves away to a certain extent. So some species are, as babies, mobile. And of course, the moment that they settle down, and become sessile and grow, they are no longer moving. So morphodynamics are very important. Look at this, these are the same species. Look at the different influence of the water. And also physiologically looking at these charts… very interesting… and I have a whole dry cabinet filled with sponge samples, and from all the literature that I was reading, the most interesting one was from Florida, the report of the sponge divers. They say clearly that they know from experience that where the water is calmer, and less turbid, and not so deep, then the smaller sponges are the softer ones. And this is exactly what you see here also with the morphodynamics depicted here – you see the influence of rough waters on the very same species, and then you can imagine how the primary and secondary fibres are aligned accordingly.

This is the glass sponge again. In order to explain it, this is similar to engineering. You have to withstand the vertical forces and horizontal ones, and diagonal ones, so that it is not collapsing. And usually humans design that way also… This is a turtle skull… it is just a fairly massive piece of bone. But the opposite is what you can do in the future – more or less, you make only skin, and you fill it, graded multi-functionally, with lattices.

And nowadays, we have another circumstance – additive manufacturing helps you a lot. You can print live cells. But again, the most important thing is the geometries. That is why I am focussing on this research. Because when you know the three dimensions and the geometry, you can also print the collagen of a patient, which has been taken from that person, and in that way you can create their own customised implants. And that is much more interesting than any artificial material that one might be using.

In Shenzhen airport I found that interior of a ceiling. I know some sponges that are built like the Shenzhen airport ceiling. But these are not soft sponges. And this image depicts a bottle opener where the rigid sponge structure has been applied, once again made of titanium alloy.

Reproducing sponge lattices

I should say briefly that synthetic sponges are totally different-looking when viewed close-up, as compared with natural sponges. Therefore I am surprised that they have been so successful… they have nothing to do with natural sponges. The coloured ones here are the ones which are from Singapore, partially even manufactured in Singapore. As you see, they all have straight struts, and have nothing visually in common with a natural sponge. And the biomaterials which are currently researched from industry, like collagen and chitin for printing, are very promising, but again the most interesting thing will be the material that is taken from patients themselves and here you see a couple of dozen lattice designs that we designed ourselves. They are all directly derived from the sponges that we were researching, and I shall spare you the torture of all the maths behind them. I shall show only two things. In the beginning you may have seen that this is a kind of bifurcation of Y-shaped joints in the *Spongia officinalis*. So we printed it, with a diameter similar to the sponge, about 35 microns, which is very small… you can't do it in any other way… And then we did it at a larger scale, in nylon. Before, we had done finite element analysis to see how our predictions are. And then you see a certain reading of stress strains. And on the opposite, that we increase the diameter and the geometry drastically. And that gave us a latticework that was several times stronger. We have done that for this couple of dozen sponge lattices. Now we know exactly – regardless of the material – what changes when we scale proportionally, when we increase the thicknesses of the struts. Plus we have a catalogue of about 32 different geometries, as a regular module which can be added in 3D, and can serve as a sponge filling in between two skins. And we have also tested the skins on both sides, to identify how they are changing their behaviours.

This is the world map of the origins of sponge research papers. I believe that we read several hundred papers from more than one hundred institutions all over the world during the course of our work.

I conclude with this photograph of part of our sponge team. Again to say that not only have we designed the algorithm of this morphological box of all the sponge lattices, but we have also tested them in the biomechanical lab of the National University of Singapore, so we know exactly their behaviour. And the next application from this summer onwards is the bone plates. They are actually, as I speak, being printed in titanium alloy, and for safety reasons they are X-rayed for defects; before any animal or human being is receiving them, there are hundreds and hundreds of mechanical tests taking place, for reasons of responsibility.

So, that’s it. Thank you for your patience.

---

* Paper transcribed from audio recording

E-mail: thallemer@ust.hk