Bio-Inspired Self-Actuating Composite Materials

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Additional information is available at the end of the chapter

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1. Introduction

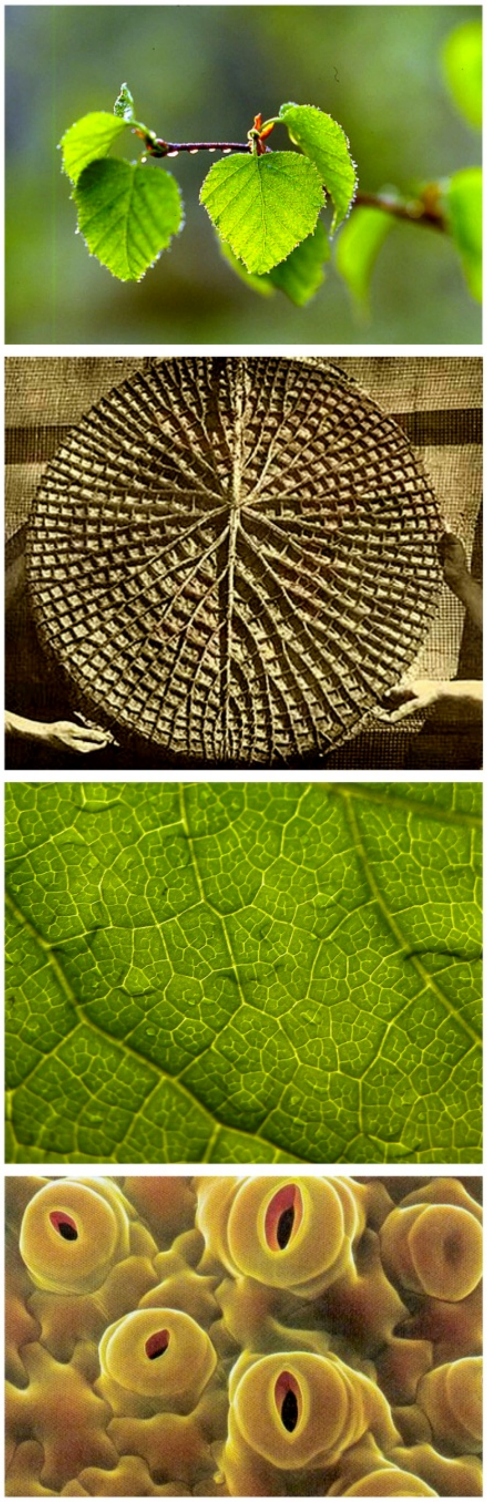
Self-organisation is a process through which the internal organisation of the system adapts to the environment to promote a specific function without being controlled from outside. Biological systems have adapted and evolved over several billion years into efficient configurations, which are symbiotic with the environment.

Form, structure, geometry, material, and behaviour are factors, which cannot be separated from one another. For example, the veins in a leaf contribute to the overall form of the leaf, its structure and geometry. At the micro scale the fibre material organisation compliments to the responsive behaviour of the leaf. Therefore, the veins display an integral coherence within the multiple functions they perform which could be termed as 'Integrated Functionality'. Integrated Functionality occurs in nature due to multiple levels of hierarchy in the material organization.

The premise of this research is to integrate sensing and actuation functions into a fibre composite material system. Fibre composites, which are anisotropic and heterogeneous, offer the possibility for local variations in their material properties. Embedded fibre optics would be used to sense multiple parameters and Shape memory alloys integrated into composite material for actuation. The definition of the geometry, both locally and globally would complement the adaptive functions and hence the system would display 'Integrated Functionality'.

2. Less is more: Organization strategies in organic composite materials

Cellulose, collagen, chitin and silks are the only four types of fibrous tissues found in natural constructions (Figure 2). Biology is capable of building all living organisms using only these four materials. It does so, without further variation than changing the arrangement and organization of the fibres in the bonding substance to adapt to function specific requirements.



1.a -http://cybele.bu.edu/index/leaf.jpg
1.b-http://www.buffalogardens.com/historical/ Crystal_Palaces/body_crystal_palaces.html
1.c-http://www.mjausson.com/2003/img/ walk24Jun03/14gunnera_dt.jpg
1.d - http://universe-review.ca/I10-22a-stomata.jpg
(accessed on May 4th 2006)

Figure 1. Series of images featuring from top: hibiscus leaves, the structure at the bottom of a lily pad, the vein pattern of a leaf, and a micro-photo of stomata which aids photosynthesis.

Living tissues have the capability to adapt to constantly changing environmental conditions. This is achieved through iterative feedback loops, which sense, record, inform and instruct the fibre composite to alter its current configuration towards an optimized one.

2.1 a - Emergence: Morphogenetic Design Strategies- Architectural Design, Academy Editions, London, Vol. 74 No 3 Issue May/June 2004, p. 4
2.1 b - Drew, Philip- Frei Otto – Form and Structure, Granada, London, 1976, p. 22
2.1 c -http://nanotechweb.org/articles/news/1/11/5/1/0611102 (accessed on Jun 12th 2009)
2.1 d- http://upload.wikimedia.org/wikipedia/ commons/a/ab/Spider_web_with_dew_drops04.jpg (accessed on Jun 12th 2009)

Figure 2. There are only four types of fibres in natural organisms: collagen, cellulose, chitin and silk.

In natural constructions, material is being continuously removed from places where it is not required and deposited where it can contribute to maintain the structural integrity of the structure. This concept was summarised by D'Arcy Thompson as 'growth under stresses'. Such a differentiated distribution process of fibres emerges through sensing the patterns of loading, or stresses constantly received by the natural organism.

Material self-organization and real-time optimization are both processes present in the formation and adaptation of biological tissues. They are termed as 'thigmo-morphogenesis' and are responsible of the resultant high performance and enormous capacity, found in natural fibre composites, to deal with unprecedented environmental conditions, unlike man-made composite materials commercially available till date.

Thigmo-morphogenesis refers to the changes in shape, structure and material properties that are produced in response to transient changes in environmental conditions. We are all familiar with the fact that many plants are capable of movement, sometimes slow as in the petals of flowers which open and close, tracking of the sun by the sunflowers, the convolutions of bindweed's around supporting stems, snaking of roots around obstacles; sometimes visible to the eye, as in the dropping of leaves when mimosa pudica is touched, and exceptionally very rapid, too fast to be seen, as in the closing of the leaves of the venus flytrap.

In all these examples, movement and force are generated by a unique interaction of materials, structures, energy sources and sensors. Cellulose walls of parenchyma cells non-lignified, flexible in bending but stiff in tension, constitute the material; the structures are the cells themselves and their shape with the biologically active membrane that can control the passage of fluid in and out of the cells; the energy source is the chemical potential difference between the inside and the outside of the cells; the sensors are as yet unknown. These systems are essentially working as networks of interacting mini hydraulic actuators, liquid filled bags which can become turgid or flaccid and which, owing to their shape and mutual interaction translate local deformations to global ones and are also capable of generating very high stresses. Similar mechanisms can be seen in operation when leaves emerge from buds and deploy to catch sunlight. How to package the maximum surface area of material in the bud and to expand it rapidly and efficiently is the result of smart folding strategies, turgor pressure and growth. [1]

http://www.tucsongardener.com/Year02/Fall2002/ photos/sensitivefold.JPG

Figure 3. Undisturbed delicate leaves of the sensitive plant mimosa pudica, which closes its leaves when lightly touched.

3. Alive: Hypothesis behind a smart composite material

The research presented herein proposes a bio-inspired synthetic self-actuating fibre composite, which emulates the morpho-mechanical processes found in natural fibre tissues, for its application to architectural constructions. The resulting material had to have integrated sensing capabilities and actuation competences, to be able to dynamically adapt to transient changes (Figure 4).

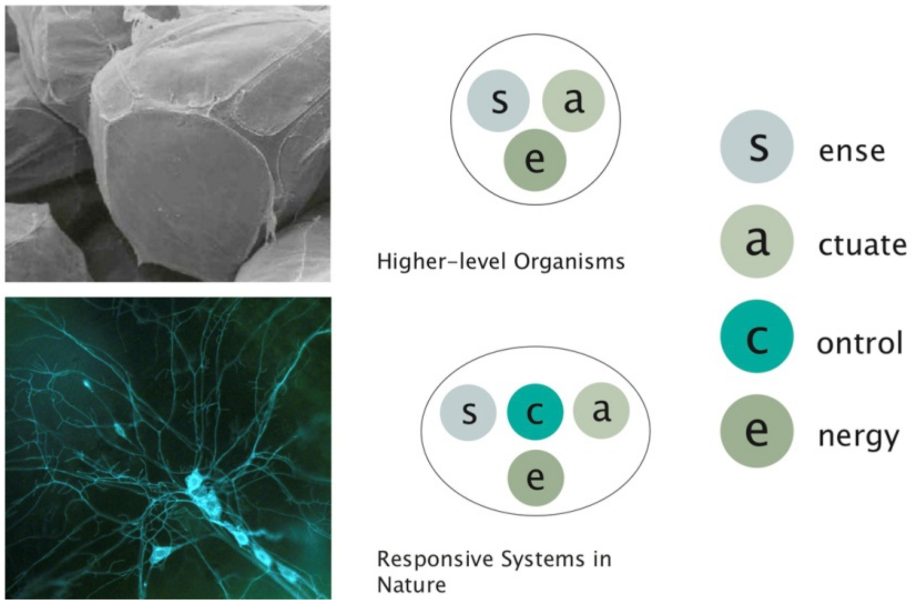


Figure 4. Diagram showing the different adaptation strategies found in natural organisms. Control being the main differentiator.

Fibre optics would be used as sensors and shape memory alloys (SMA) as actuators (Figure 5). Glass fibre mats constituted the reinforcement layer for the resin-based binding matrix, in which fibre optics and shape memory alloys were embedded. Experiments were however performed substituting fibre optics for thermocouples and strain gauges, which sensed and transmitted the energy necessary for the actuation to the shape memory alloys. Energy is supplied through a source of external heat, which forms part of the experiment setup. Further research reveals that, in hot-dry climates, sun radiation could be used as the main heat source to enable actuation, with only a small percentage of the total energy being supplied by external sources at certain periods of the day when exploiting solar heat is not possible.

In structural engineering, fibre optics is used as monitoring devices capable of measuring strain, temperature and humidity. One of their great advantages relies on their small size and fibred geometry, which converts them in perfect candidates for thin-wall structures such as fibre composite matrixes. Their receptive ability is achieved by designing the fibre optic cable to be sensitive to a specific parameter. The light pulse sent through the cable is received and further analysed by the processing unit to determine the magnitude of strain or temperature measured. Fibre optics was however substituted by strain gauges and thermocouples in the series of experiments implemented to test the performance of the self-actuating fibre composite material presented herein.

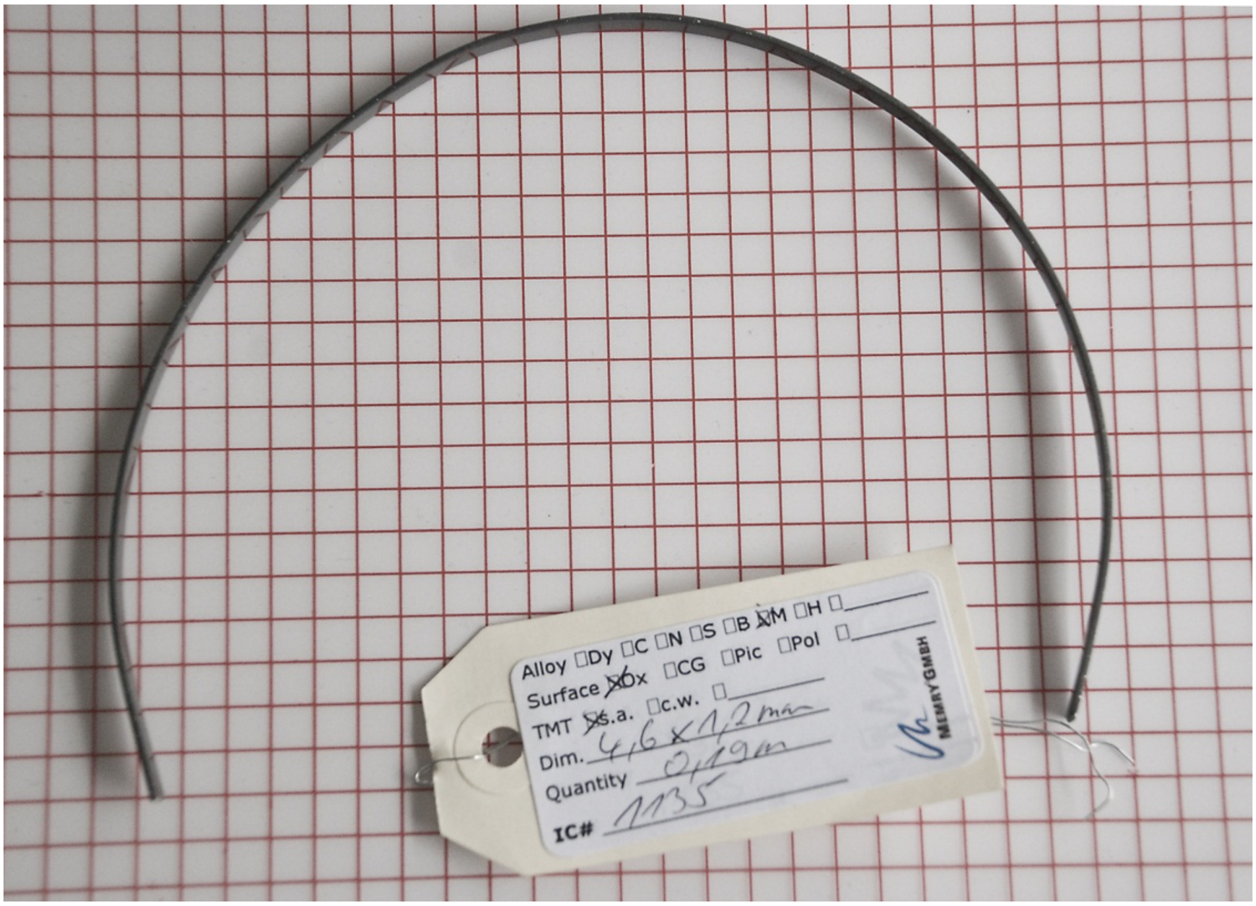


Figure 5. Nitinol based shape memory alloy. Shaped as a ribbon featuring an actuation temperature of 65°C.

Strain gauges are resistance-based sensors employed to measure variations in length of a parent component, factored by the component's original length. Strain gauges consist of a thin wire of metal foil, wrapped across a grid, which is also attached to a thin flexible backing material impregnated with glue, for adhesion to the parent component for which strain is to be monitored. This setup allows the wrapped wire to stretch or compress thus, detecting elongations and contractions felt by the parent component (Figures 6 and 7).

4. Experimental: Understanding the behaviour of SMAs

Nitinol (NiTi) is a specifically manufactured alloy of nickel and titanium, which has the ability to generate significant force upon changing shape. NiTi shape memory alloys can exist in three different crystal structures or phases called martensite, stress-induced martensite and austenite. At low temperature, the alloy exists as martensite, which is weak, soft and highly deformable. Stress-induced martensite (or super elastic NiTi) is highly elastic and is present at a temperature slightly higher than its transformation temperature. The austenite is the strongest, higher temperature phase, present in NiTi. Most of the physical properties of austenite and martensite vary during phase transformations; among these properties are the Young's modulus, the heat capacity, the latent heat and the thermal conductivity.

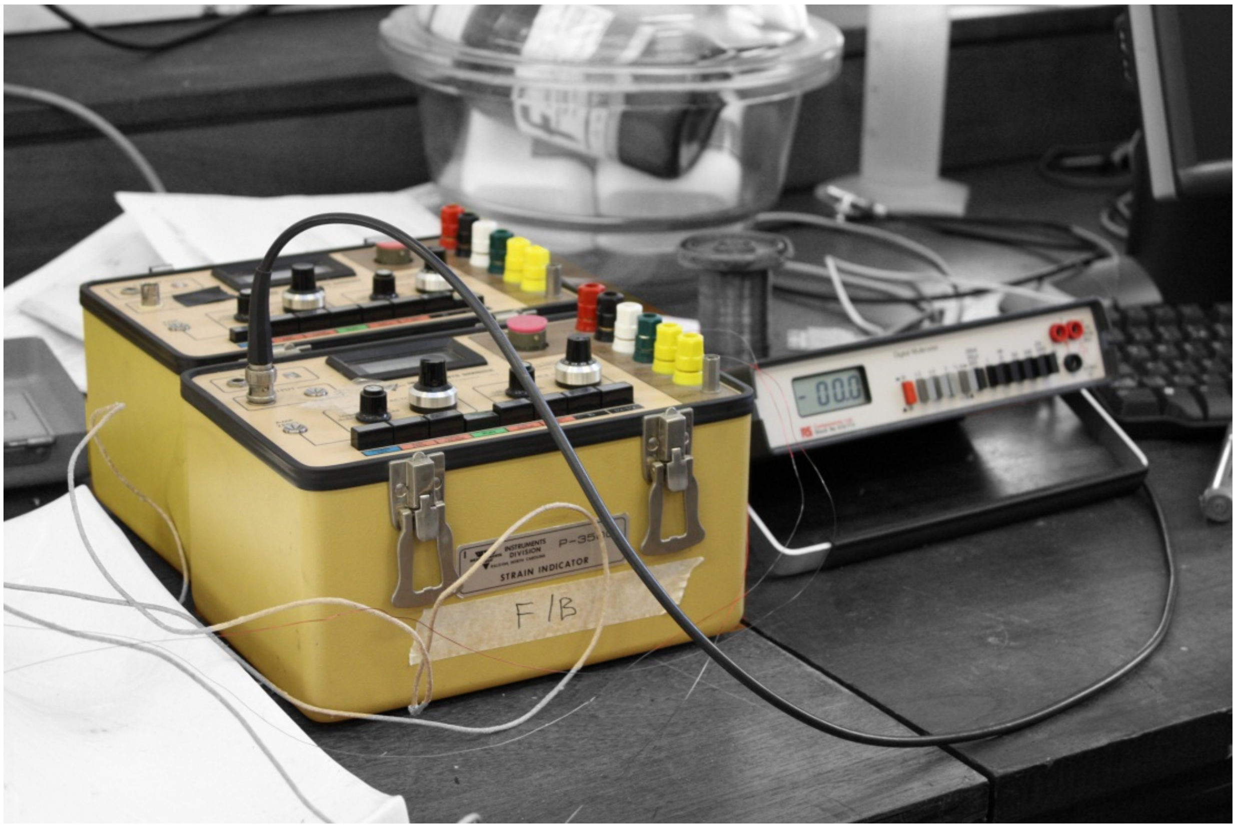


Figure 6. Picture illustrates the calibration process of the strain gauges processing unit.

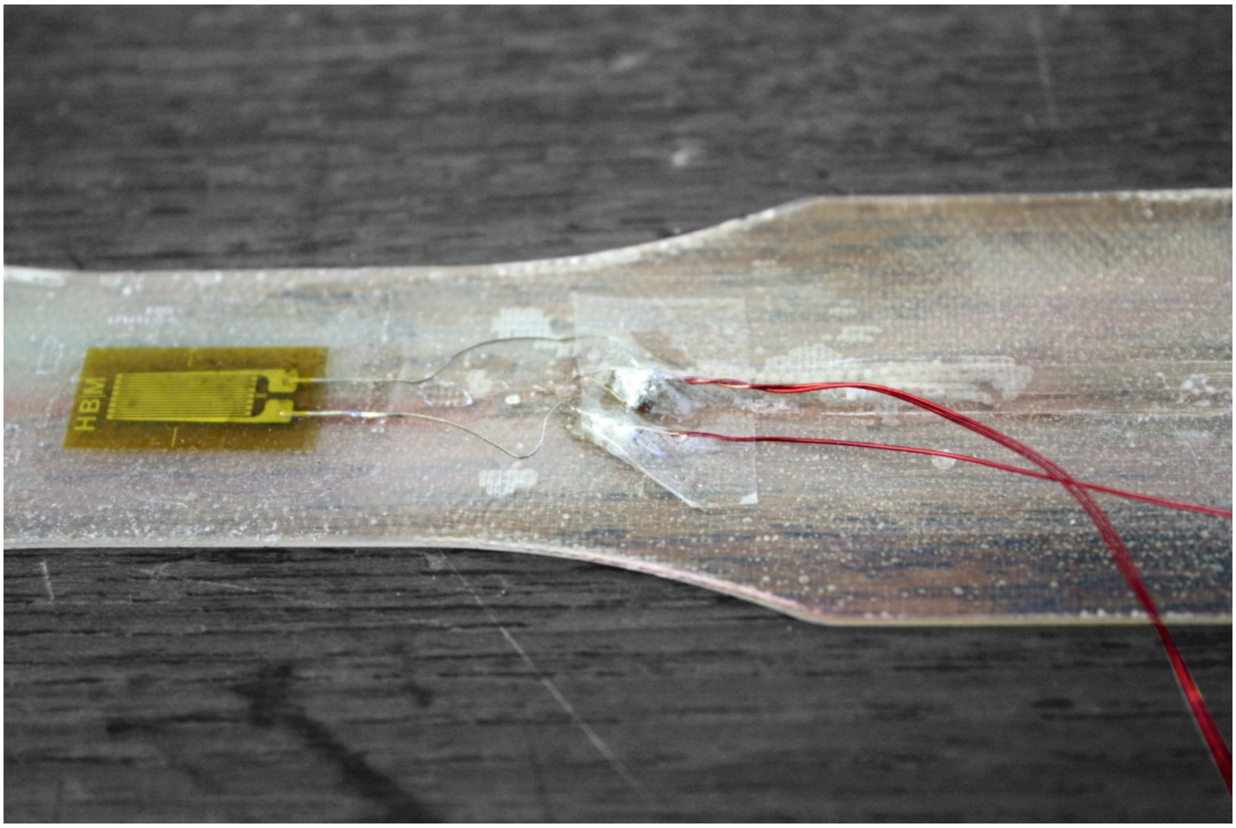


Figure 7. Picture features the strain gauge during its calibration and testing on a polyester strip.

Shape setting is essential to train the NiTi alloys to remember a specific shape. An actuator element designed for a particular purpose generally requires the setting of a custom shape. Shape setting is similar in all forms of nitinol, such as, wires, ribbons, strips, sheets, tubes or bars. It is accomplished by constraining the nitinol element on a mandrel or a fixture of the desired shape while applying an appropriate heat treatment. The heat treatment parameters and the properties of the actuator element are critical for the consequent behaviour of the NiTi, and usually need to be determined experimentally. In principle, temperatures as low as 400°C and heating times as short as 1 to 2 minutes are sufficient to set the shape, but generally one uses a temperature closer to 500°C and a heating time period of at least 5 minutes. Rapid cooling of the alloy is preferred via a water quench or rapid air-cooling. Higher heat treatment times and temperatures will increase the actuation temperature of the alloy and often results on sharper thermal responses. There is also an accompanying decrease in the ability of the actuator to resist permanent deformation. [2]

The first set of experiments focused on understanding the process of shape setting in SMAs outlined above, and their actuation behaviour against temperature. These were especially motivated by the need to quantify their lifting capacity against time for their latter integration in the fibre composite matrix. The SMAs used for these experiments were ribbons with an actuation temperature of 65°C, 1.2mm thick, 4.6mm wide and 270mm long.

The shape setting process required the SMAs to be heated at 500°C for at least 5 minutes. The SMA ribbons were trained by fixing them around metal pipes, which helped maintaining the SMAs in place during the heating process. They were subsequently removed from the oven and immediately immersed in cold water whilst maintaining the imposed bent shape throughout the cooling procedure (Figures 8 and 9).

Figure 8. Shape memory alloys and mandrels inside kiln after heating process had finalised.

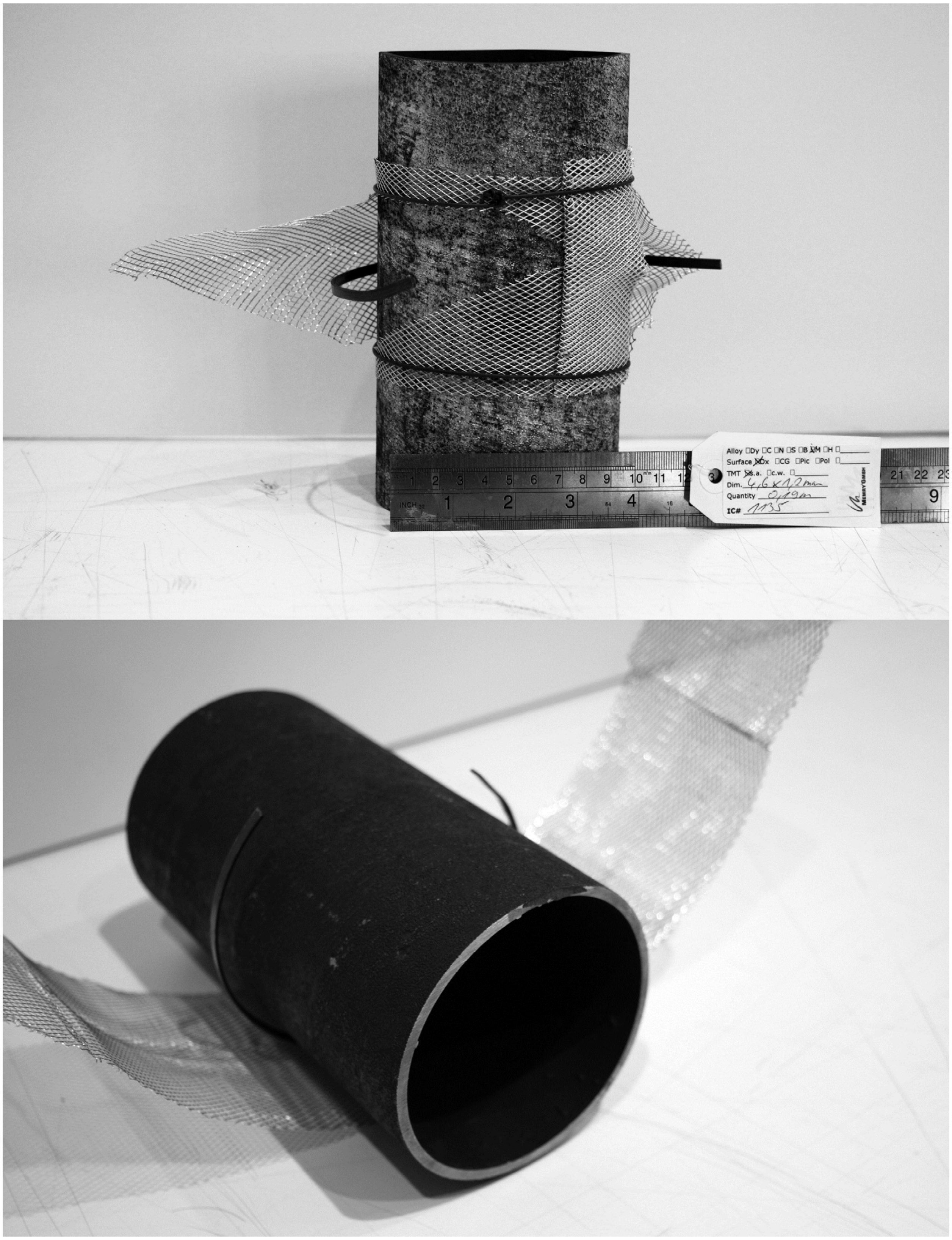


Figure 9. Shape memory alloy and mandrel following its removal from the kiln, after the cooling process.

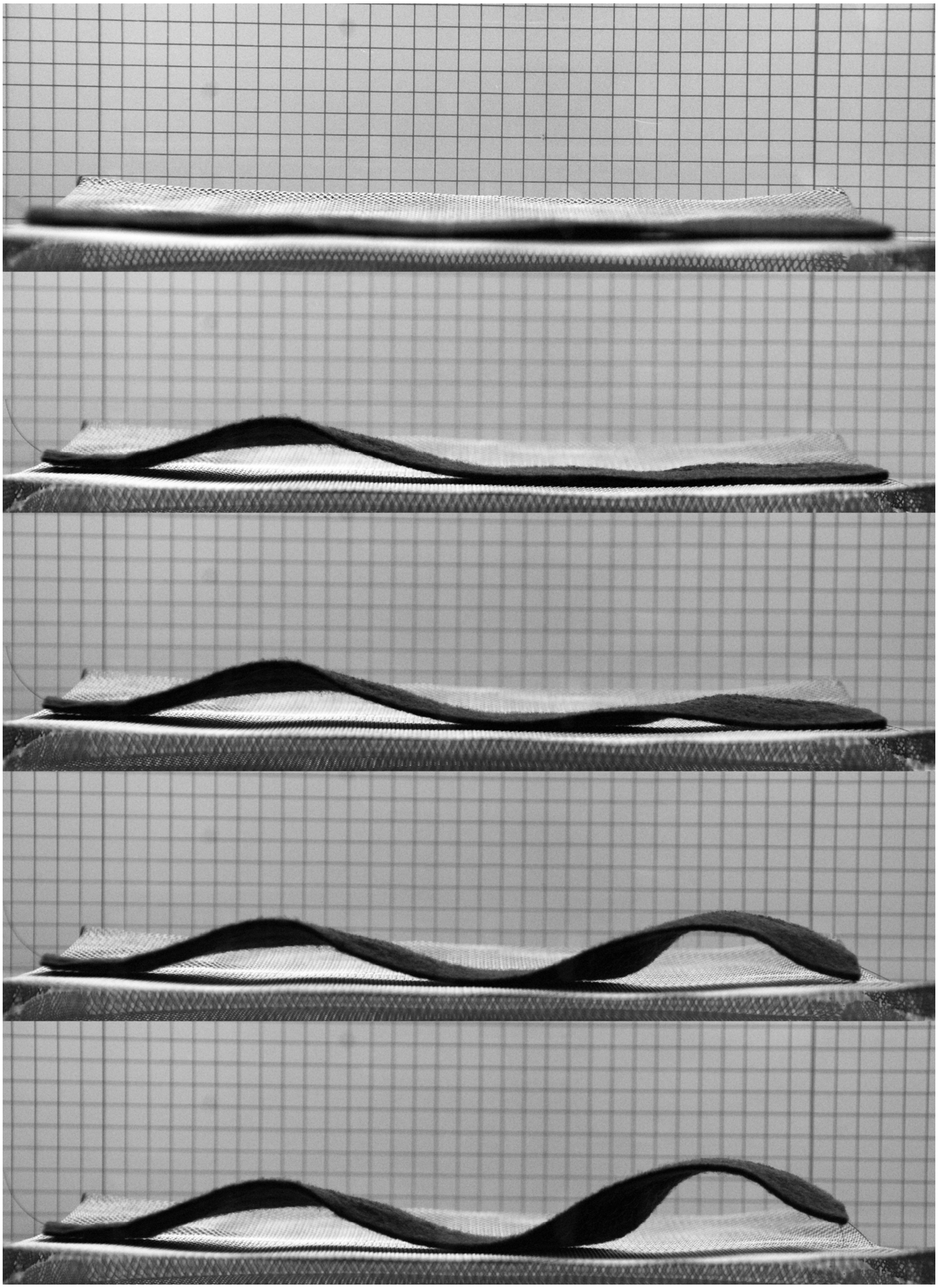


Figure 10. Sequential photograms featuring the actuation of the shape memory alloy ribbon sewed onto a piece of felt.

Subsequent experiments focused on demonstrating quite simplistically the actuation abilities of our SMAs. We first wrapped the SMAs ribbons with a piece of felt to better illustrate the resulting shape change. The outcome, featured in Figure 10, was exactly what we expected, with the SMA achieving the 'memorized' shape quite rapidly. The experiment that followed tested the behaviour of the actuator under the tension exerted by a thin fabric membrane. The fabric was anchored to a circular frame installed on a planar surface with a heat-gun pointing straight downwards onto the alloy. The ribbon curved consistently, pulling the thin membrane up steadily, as soon as the actuation temperature was reached. Figure 11 illustrates the results. While these were both very simplistic experiments, they guided our research towards quantifying the actuation force of our SMAs when embedded in a fibre composite.

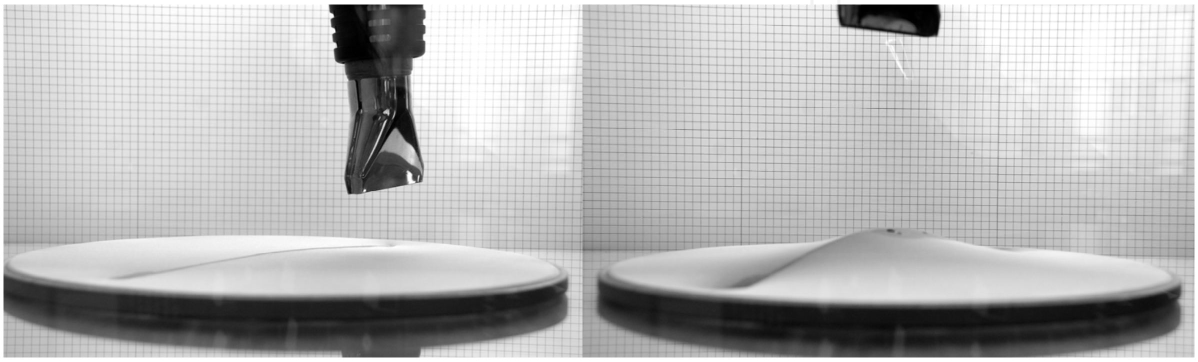


Figure 11. Sequential photograms featuring the actuation of the shape memory alloy sewed to a thin fabric membrane.

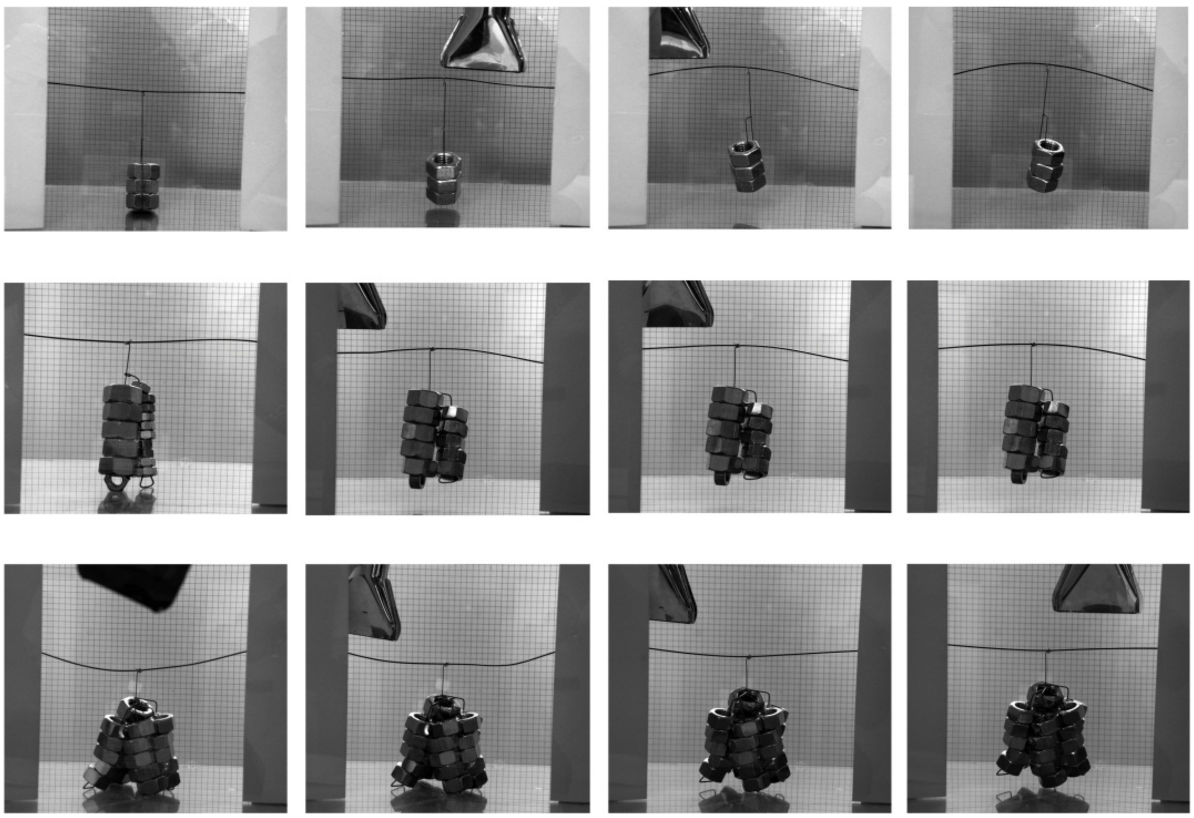


Figure 12. Sequential photograms featuring the load lifting tests undertaken.

The ribbon was this time set up as a simply supported beam under sequential loading increments, the aim being to quantify the SMAs actuation force against time (Figure 12). Whenever the load was increased, the actuation time was measured. Each load increment was quantified as 0.56 N, i.e. the weight of the nuts used. Figure 13 shows the load-time relationship when actuation occurred, lifting up the ribbon and the imposed weights. Experiments proved that the ribbon under testing could lift a load of 8.83N, which equates to 100 times its self-weight. The time taken to lift the first nut was 8 seconds, while lifting the group of nuts weighting 8.83N was 18 seconds. Assuming the 8 seconds for the first lift is the time it takes the ribbon to achieve the actuation temperature, the actual actuation time to lift 8.83N was 10 seconds. This series of experiments provided us with substantial information on the behaviour of the SMAs and particularly, how much force they could exert and how rapidly.

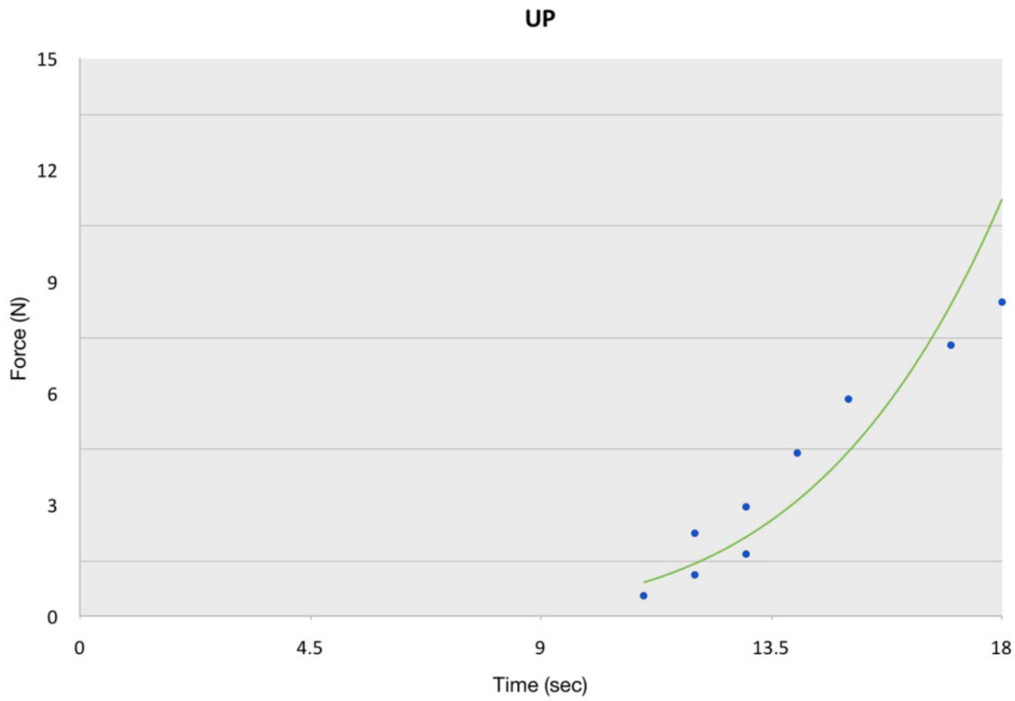


Figure 13. Graph featuring the load lifting capacity of the ribbon, against the time taken to actuate.

The next step was to calibrate the curvature change of the SMAs in relation to temperature. We had purchased ribbons with a theoretical actuation temperature of 65°C. However, we knew that the behaviour of the alloy and ultimately its actuation temperature could have been altered during the shape training process. A simple experiment using a thermocouple and a unit controlling the temperature of the alloy served to measure the curvature of the alloy at different temperature increments (Figure 14). The experiment demonstrated that the shape change did not occur instantaneously; instead, it was a steady process that started at 38°C, with the alloy reaching its maximum curvature at 58°C, as supposed to its theoretical actuation temperature of 65°C. It was clear that the training regime of the alloy had an impact on its later behaviour. The high curvature of the trained shape could have also altered the resulting actuation performance. This test also provided us with key data regarding the maximum curvature change that the alloy could achieve when setup freely. The outcome of this calibration exercise served to feed the construction of the final prototype.

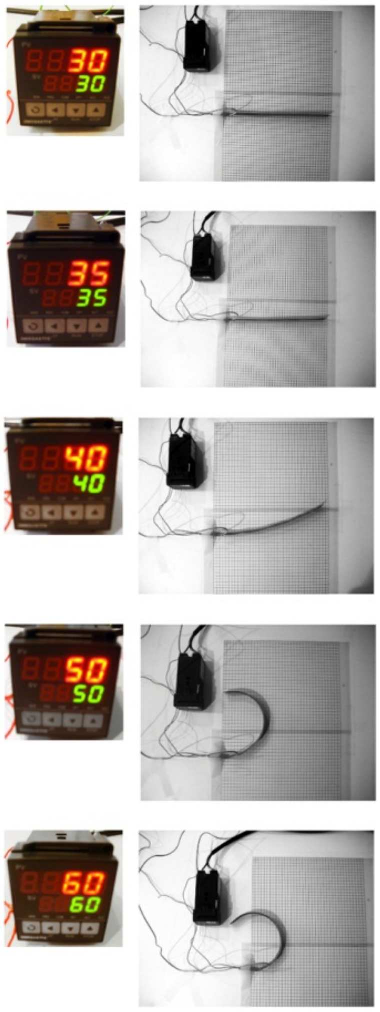


Figure 14. Series of photograms featuring the calibration of the shape memory alloy ribbon. Actuation temperature and curvature changes were measured and subsequently registered to inform the building of the final prototype.

5. Composite: Building the material system

Further experiments followed the preliminary tests described above, contributing to the refinement of the final model. These were aimed to test the elasticity of different polymers, from highly deformable to more rigid mixtures. Finding a polymer with an appropriate elasticity modulus was key to achieve the intended degree of actuation in the fibre composite material. Figure 15 features a failed setup using a silicon-based composite, which resulted extremely flexible and heavy to be anyhow actuated by four SMA ribbons. The test did serve however to guide the research towards the use of polymers with higher Young's modulus.

Our final experimental model consisted of a sandwich structure made of two layers of a glass fibre mat bonded by an epoxy-based resin. A total of four SMA alloys were embedded in between the two layers of glass fibres. Figure 16 features a diagram illustrating the set up of the model.

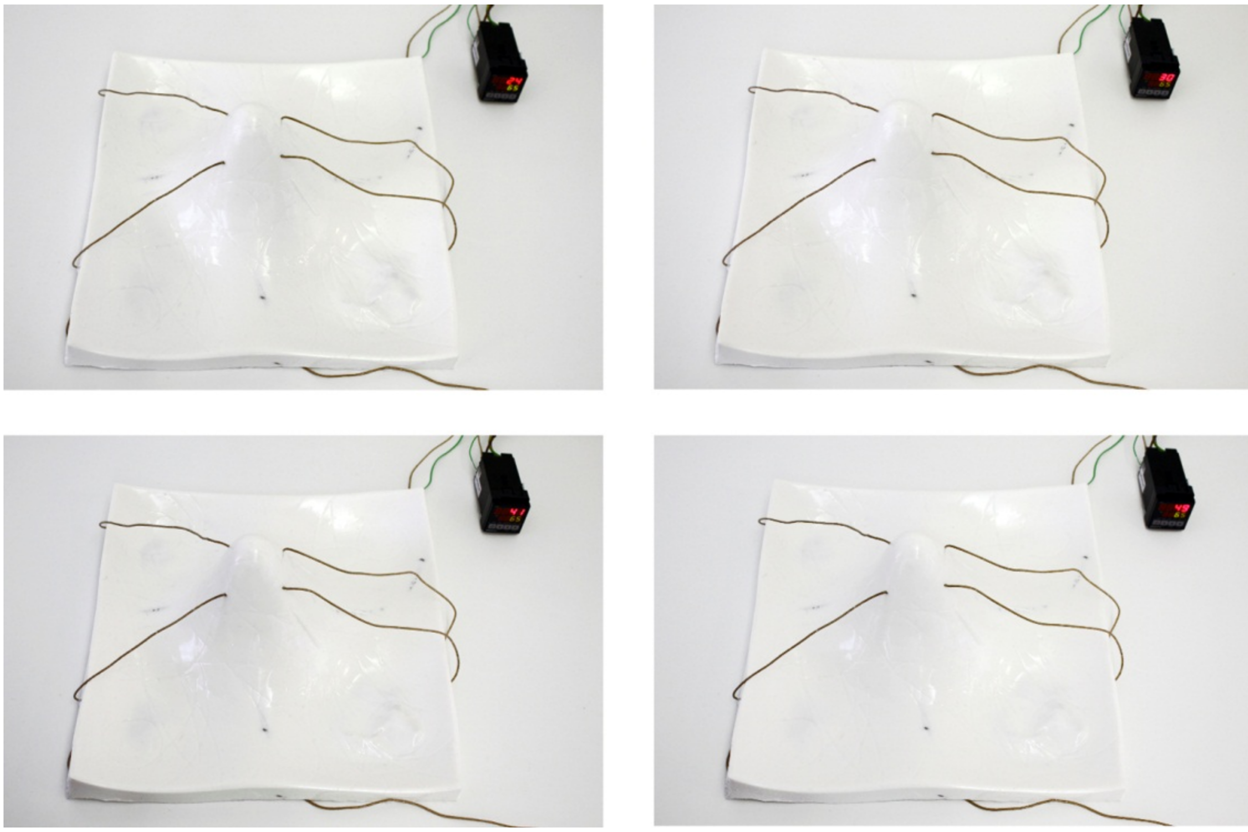


Figure 15. Sequential photograms featuring the failed experiment using a silicon-based composite.

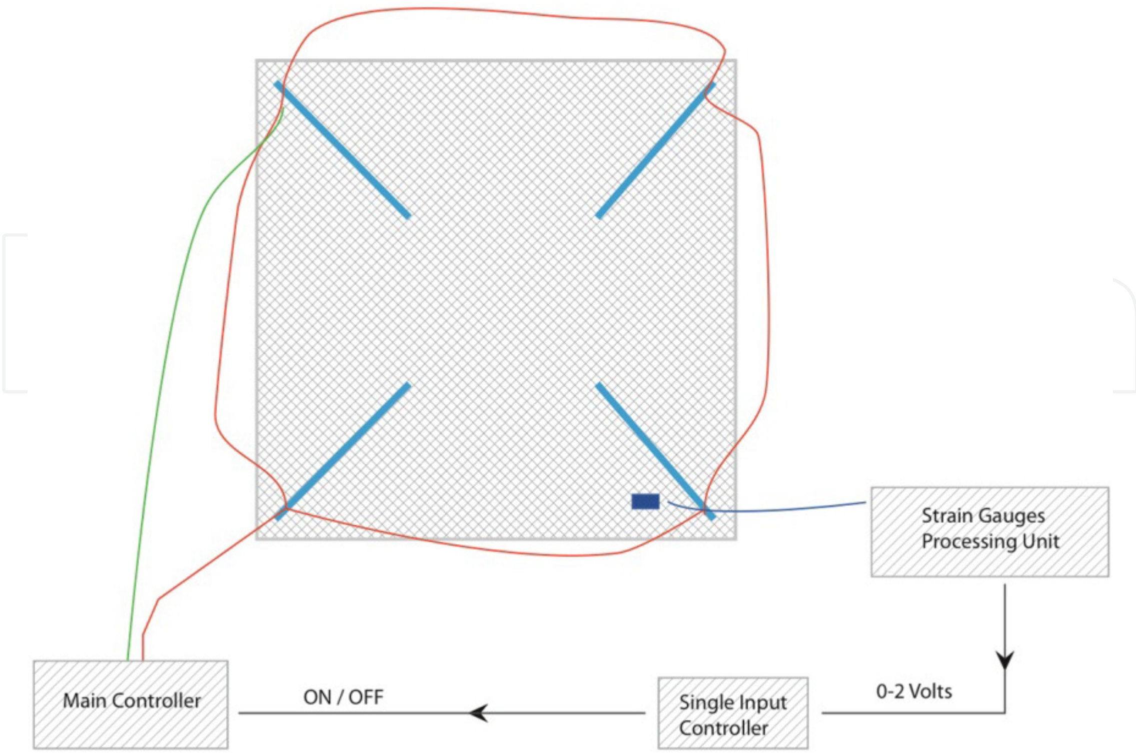


Figure 16. Diagram featuring the arrangement followed for the assembly of the final prototype.

Figure 17. Silicone heating patches used in the experiments. Advantages of the use of these patches are their lightweight, thin and flexible structure, while being able to heat up to 232°C.

Figure 18. Pictures illustrating the construction of the final prototype.

The sensing capabilities of the model were based on an active-dummy method (also known as Wheatstone's bridge) that allowed measurement of real-time changes in strain on the parent shell structure. Two gauges were then connected to a processing unit, which translated the strain signal into a voltage output of 2 volts, when elongation was detected, and 0 volts, once it ceased. This voltage was then sent to the controller unit, which turned on and off a set of silicon heating strips upon which a shape memory alloy wire was glued (Figure 17). A set of thermocouples were used to measure the temperature of the shape memory alloys as the silicon heating strips commenced to heat them. The processing unit to which the thermocouples were connected would automatically stop the heating process once the actuation temperature of the actuators was reached (Figures 18, 19 and 20).

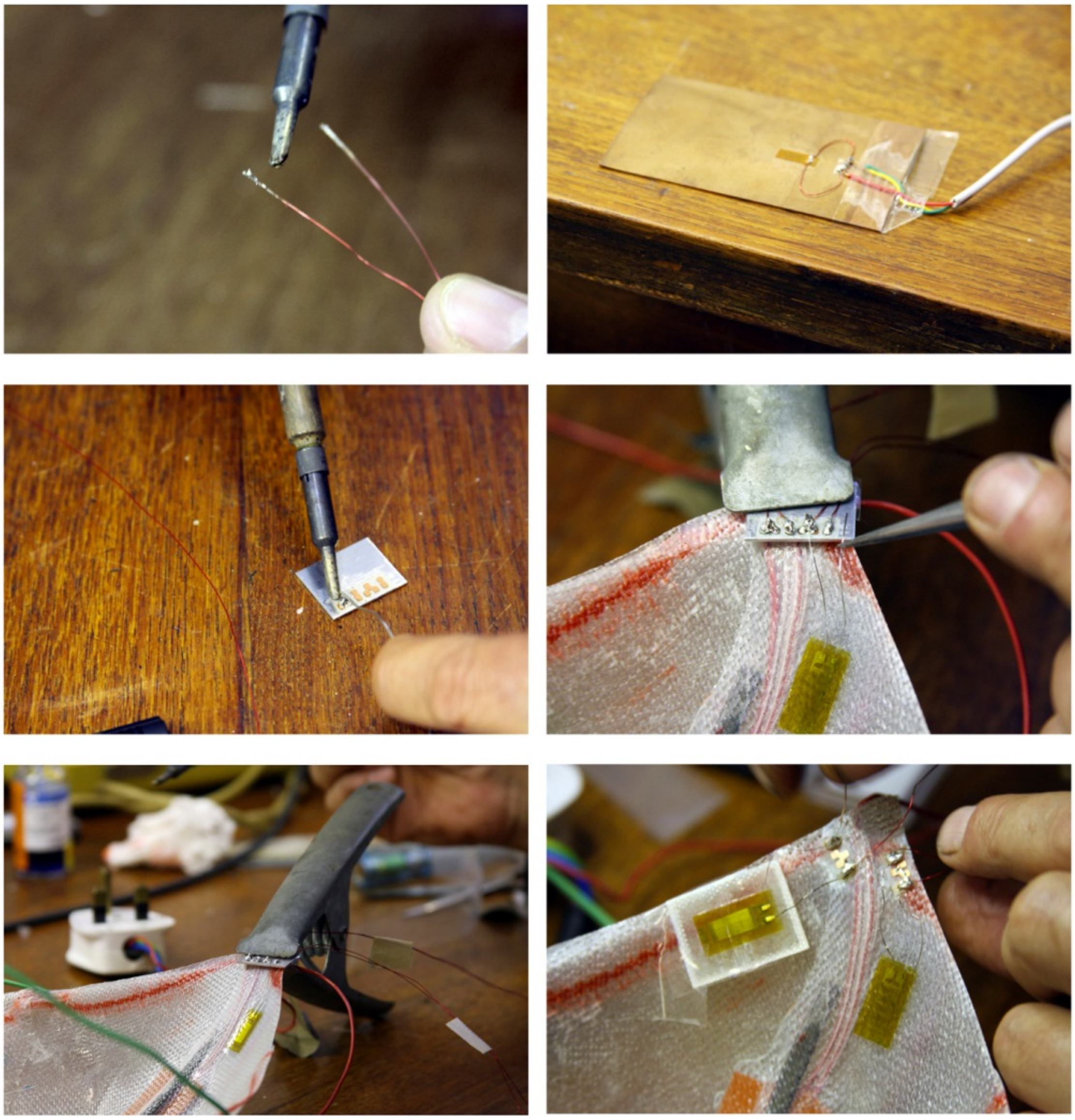


Figure 19. Pictures illustrating the soldering and preparation of the strain gauges on the final prototype.

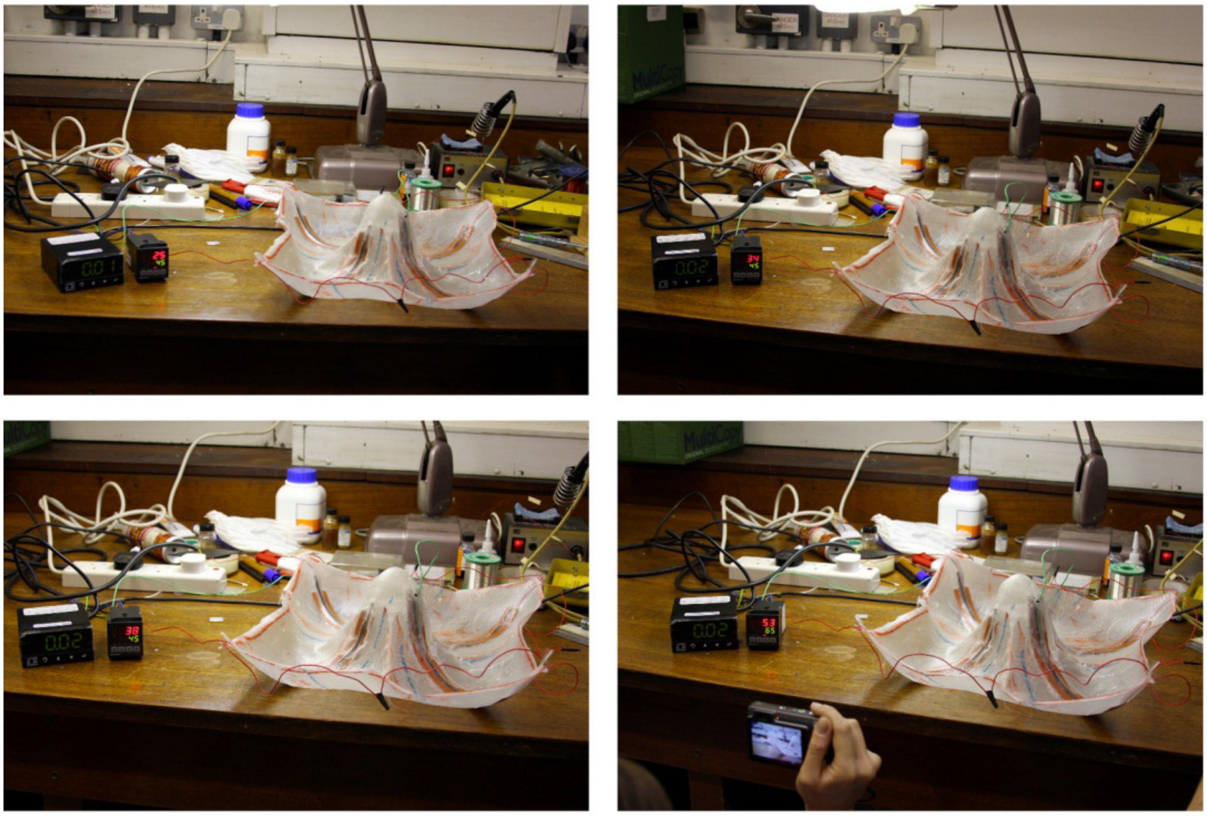


Figure 20. Series of pictures showing preliminary tests of the actuation in the laboratory.

Alternative methods to the use of silicon heating strips could have been piezoelectric fibres, which can generate electric potential in response to applied mechanical stress. The implementation of piezoelectric fibres in our setup could have potentially avoided the need for the strain gauges, the processing and control units, as well as, the heating strips.

Figure 21 features the set up of the final prototype, including the strain gauges processing unit and the different controlling devices. Figure 22 shows the actuation response of the prototype at the temperatures of 30°C, 42°C and 58°C. At 30°C the shape of the prototype has not yet been altered; it is therefore the initial shape which serves as reference of the non-actuated model. At 42°C, the strain gauges detected actuation had commenced. From previous tests, we knew that if setup freely, the alloys would start actuation at 38°C. However, the alloys were now embedded in a fibre composite, which contributed to an increase in stiffness. It was more difficult for the alloy now to start curving and as a result, to spread that deformation to the material it was embedded in. This caused a delay on the actuation of 4°C when compared to the previously tested model where the SMA did not experience external material constraints. At 58°C the prototype was about to reach its highest curvature. The shape change can be easily compared thanks to the photogram made by superimposing the actuation stages described above.

6. Architecture with smart composites

On an architectural scale, the aim was to introduce actuation not through and external heat source but by utilizing the diurnal temperature variation in the environment.

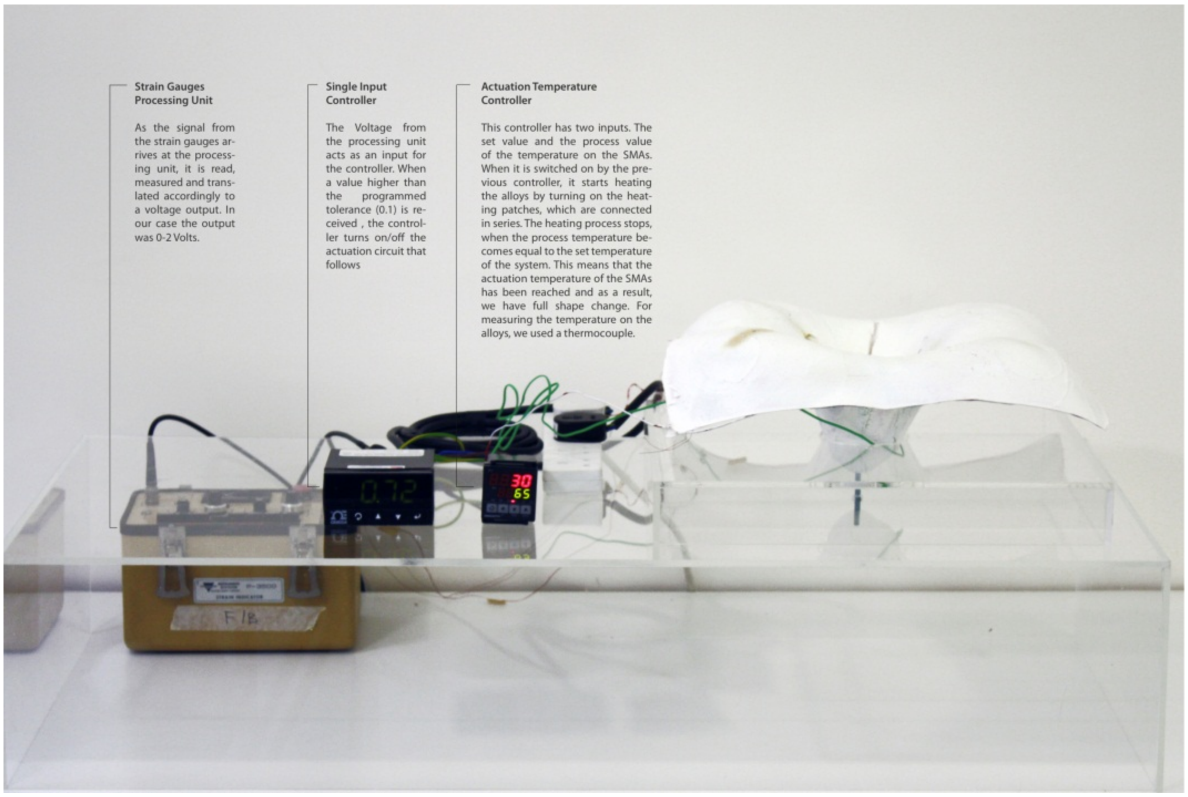


Figure 21. Final setup of the prototype including the strain gauges processing unit, the single input controller, the actuation temperature controller and the final prototype.

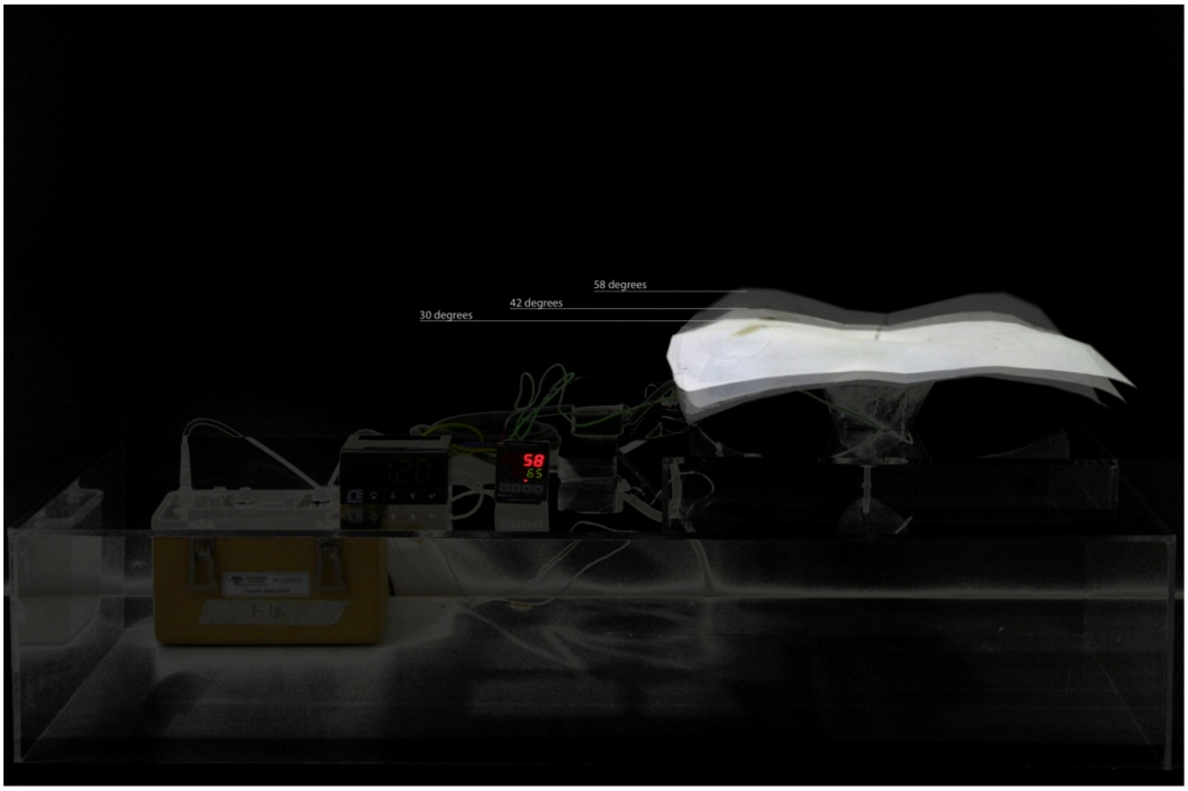


Figure 22. Superimposed photograms featuring three resulting shapes of the actuation at the indicated temperatures.

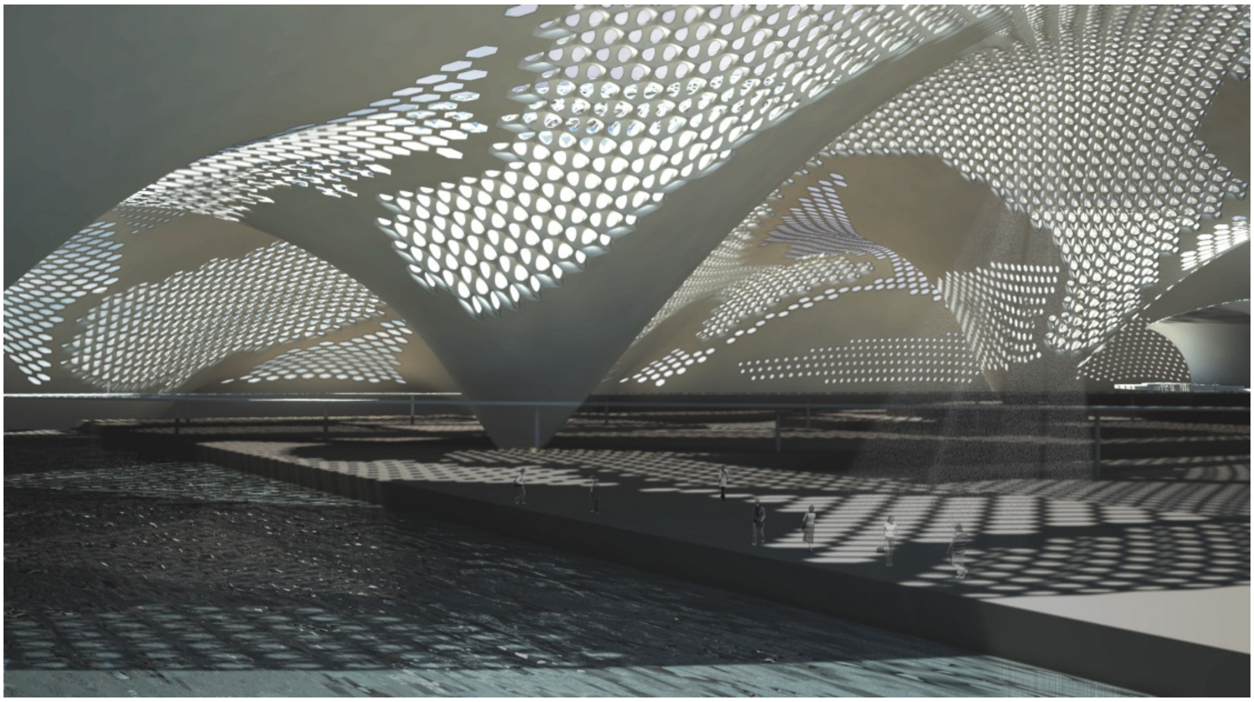


Figure 23. A view of the shell with the actuating fenestrations

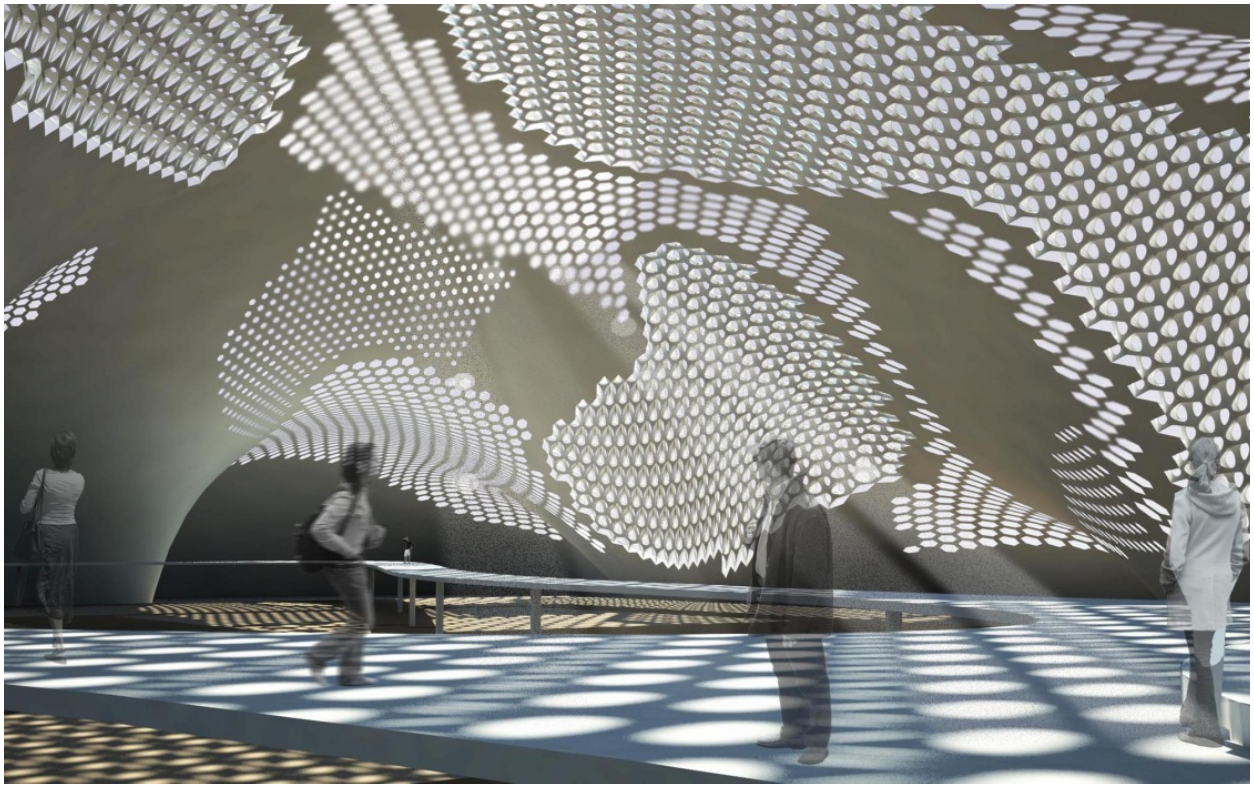


Figure 24. An interior view from the shell

Hot and dry climatic zones which have a considerable diurnal variation in temperature would be the most appropriate to exploit the environmental energy for the efficient functioning of the adaptive system. While actuation temperatures of commercially available shape memory alloys range between 30°C and 95°C, the specific alloys used for the experimental setup had actuation temperatures ranging from 35°C to 65°C. In hot and dry climatic zones the variation in atmospheric temperature is measured to range from 22°C to 44°C in the summer months. Surface temperature of the alloys would therefore easily reach the required 35°C which would initiate their actuation.

Self-actuation potential of any structure invariably necessitates integrating decision-making abilities and thus intelligent behaviour into the adaptive system. The morphological definition of the structure plays a key role in adaptation and has to be coherent with the actuation logic. The material tests and experiments conducted, establish the premise for the architectural application of the self-actuating fibre composite system developed herein. The study branches further into the utilization of such a self-adaptive material system in an architectural application, with reference to context specific climatic data (Figures 23 and 24).

The image shows a large span fibre composite shell structure with actuating fenestrations. The shape memory alloys embedded in the fenestrations allow the structure to open and close based on the external environmental conditions. The opening are strategically positioned in a manner in which they do not affect the structural stability at the same time enhance the interior lighting and wind flow pattern.

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7. References

[1] Jeronimidis, George, 'Biomimetics - Differentiation / Integration / Emergence, Sensing – Actuation –Control', - Lecture at the Architectural Association, London, 2009.

[2] Smith,S. A, 'Shape Setting Nitinol', - Proceedings of the Materials and Processes for Medical Devices Conference, pp 266 – 270. edited by S. Shrivastava, ASM International, Sept., 2003.