DDU
Digital Design Unit — Digitales Gestalten

TECHNISCHE UNIVERSITÄT DARMSTADT

APERIODIC MECHANICAL METAMATERIALS

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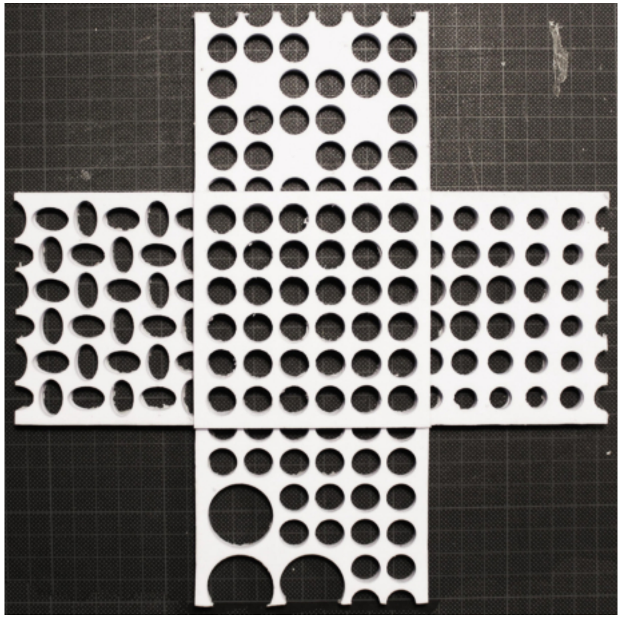


General context and aims

Metamaterials are artificial structures with properties that are defined by their structure. This article will focus on mechanical metamaterials. In mechanical metamaterials the mechanical properties are in the focus and are intended to be altered. Mechanical properties are qualities in respect of an applied force like strength, ductility or brittleness. These mechanical properties can be designed to have values which cannot be found in nature.[1] While the resulting structures are still dependent on properties like the Young's modulus or ultimate elongation of the material used to build them the constructed structure gives certain properties like an increased flexibility or compression behaviour to the metamaterial. As mentioned, these properties are not independent of the matter of which the metamaterial is made of but appear whilst using different base matters.

As substances for mechanical metamaterials ideally elastic matters like elastomers or metals are used.

Therefore, theoretically with metamaterials it is possible to design metals that contract while being compressed.

1 https://en.wikipedia.org/wiki/Mechanical_metamaterial (3.7.2017)

The metamaterials currently done research on are generally defined by a periodic array of unit cells. As a consequence, most of these materials have a regular transformation or reaction to a force. They deform uniformly as shown in most of the papers below.
An aperiodic structure of different unit cells would allow to create more specific movements in the metamaterial. Thus, it would be able to determine certain paths of movement or deformation that then can be translated into the structure of a metamaterial. This inhomogeneity in the material would allow plenty of new possibilities and applications for metamaterials.
It would allow to design decorative or functional elements for architecture that are made of one metamaterial.
These elements could transform in a certain way or show patterns on their surface. Thus, maybe creating a shading device, mechanical parts or versatile wall surfaces.

To achieve this, this research will first give an insight in previous research, then explore different manufacturing methods for different metamaterials to provide protocols and lastly apply aperiodicity to metamaterial architecture to examine its impact.

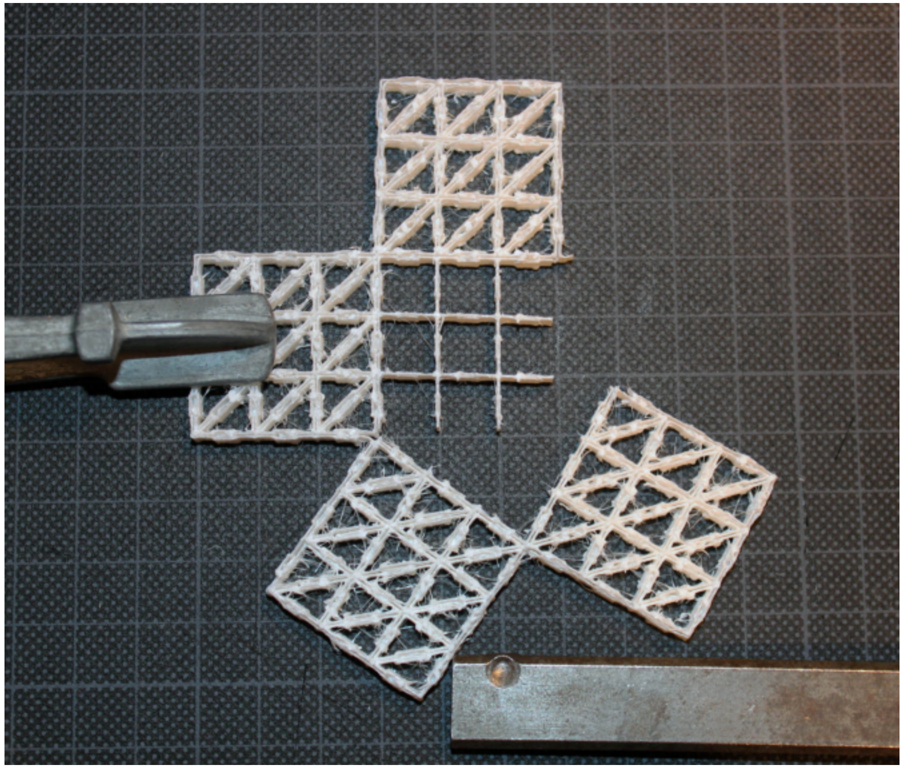


Fig. 11

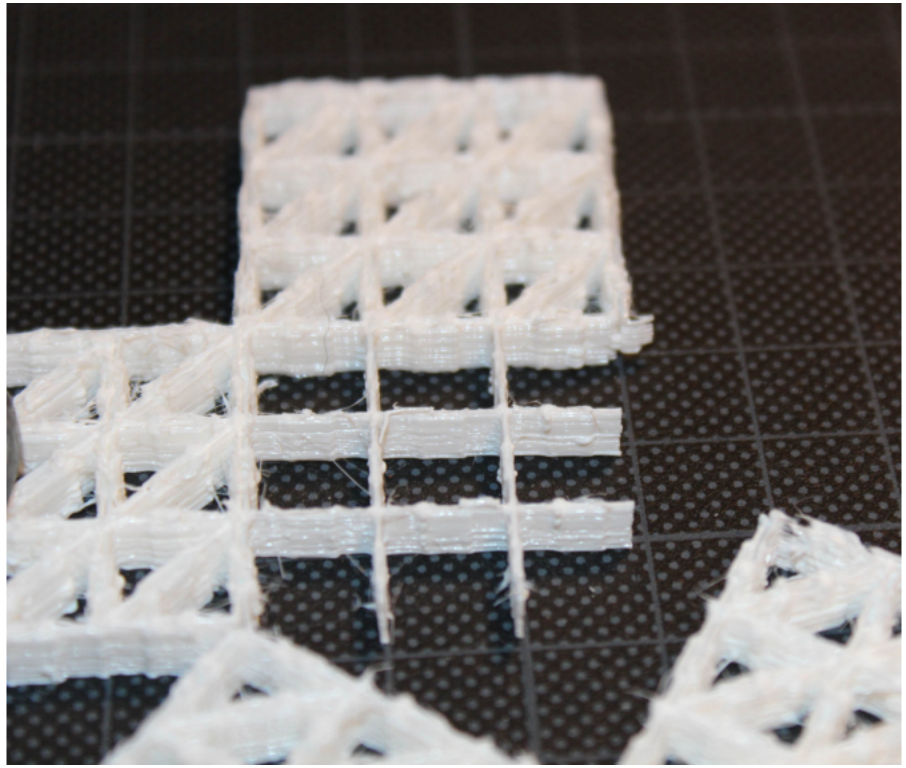


Fig. 12

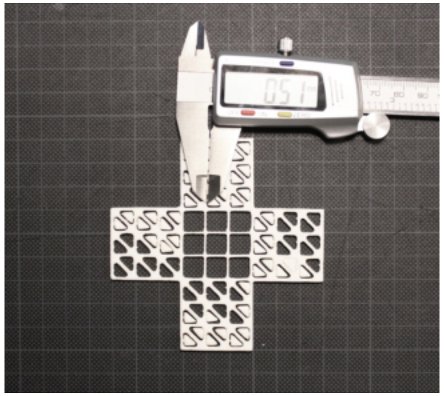
Results

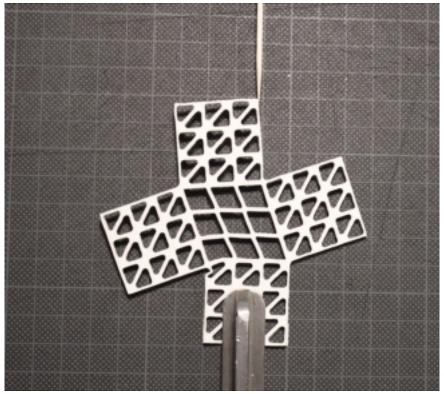
In figures 2 to 4 a force is applied in different directions. It is possible to transform the module in each of the ways. It appears that in each direction the reaction is equal.
In figures 5 to 7 the force is increased and therefore the transformation grows. As to see in relation with the lines it the background the vertical translation introduced is approximately the same size as the resulting horizontal shift of the upper member. In figure 8, at a deformation of about 19 mm the object breaks.
Looking at figure 9 and 10 it is clear that the method used by the 3D-printer creates the weakest part of the matter. The four-bar broke vertically at the points where the printer changed direction.

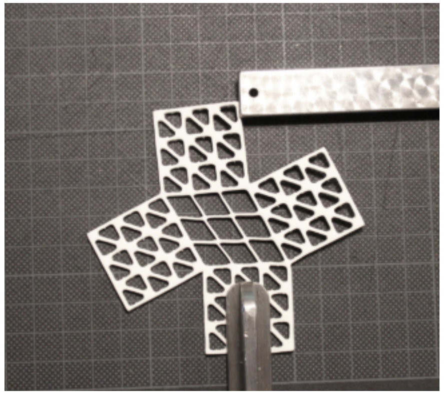
It is to observe that to transform the four-bar a strong force has to be applied. But, also with this effort the movement created is not big.

Discussion

Given that the 0.4 mm thickness of the hinge cells are the minimal dimensions the printer can print, either a printer with a higher resolution or a material easier to transform, less brittle and more elastic has to be chosen.





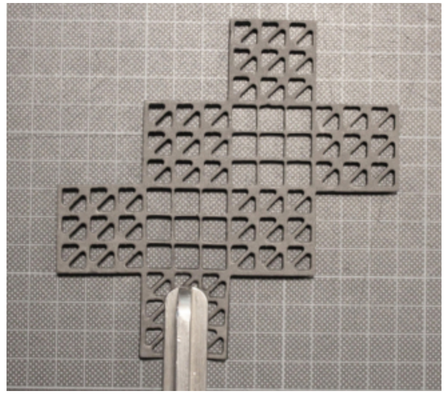


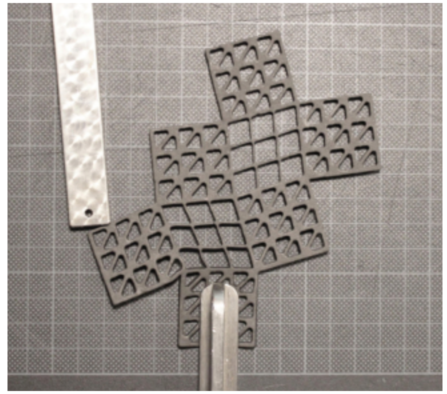
The four-bar is then tested fixating one of the rigid members with a clamp onto a board. The board contains millimetre markers to evaluate the movement.
On one of the free members a small force is applied that transforms the four-bar. Later the force is increased for multiple times in one direction until breaking point in order to see the maximum transformation and the durability of the module.

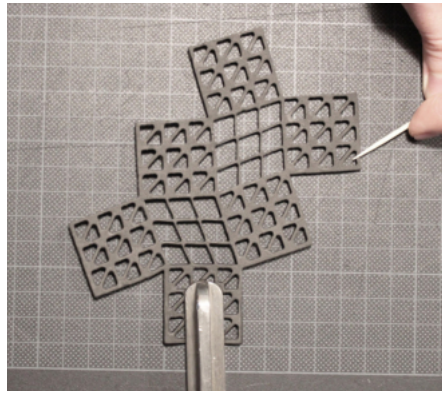
As a completion to the simple four-hinges, two combined four-hinges are produced to evaluate the resulting reaction on a force (figure YYY).

Results

For best results the laser had to have an intensity of 15% (using a laser cutter with 40W), whereas the thickness of melted foam is almost the same for each intensity. The only difference is whether the laser beam cuts through the material or not (with





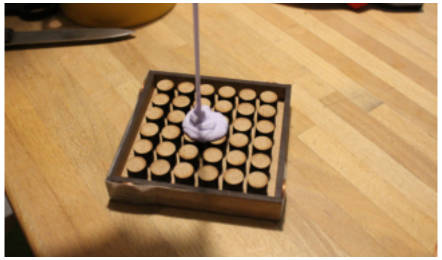


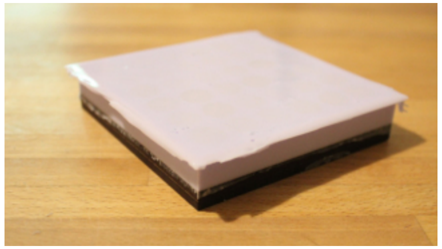
10% intensity it did not cut the 3 mm foam, with 15% it did) and how visible the stains are on the back of the material. Using an increased intensity of 90% the reflection of the laser beam at the metal grid of the laser cutter is as high that clear brown burn marks can be visible next to the cut lines.
For each of the different laser intensities an equal amount of material with a thickness of about 0,5 mm is burnt in each cut line.
While the intensity is vital, the speed is not really relevant for the result.

Discussion

In contrast to the 3D-printed model the foam specimen is not breaking. Instead, the smaller parts are folding when the force grows too high. When decreasing the force all of the hinges return to their initial position.
Also, a much lower force has to be applied to see reactions at the module.

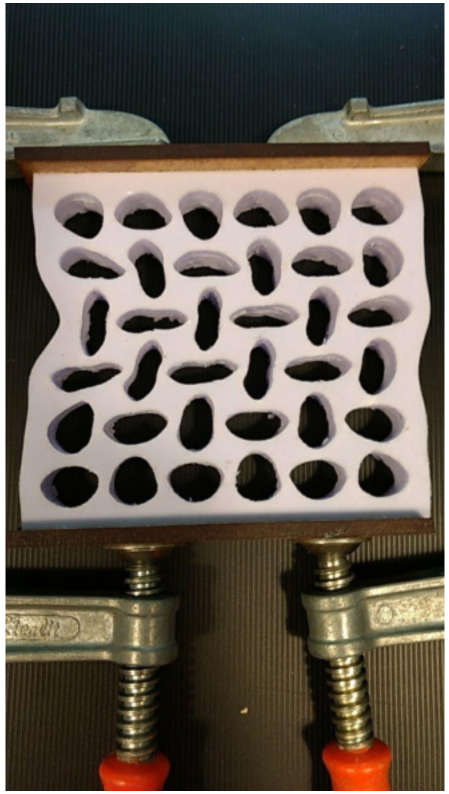
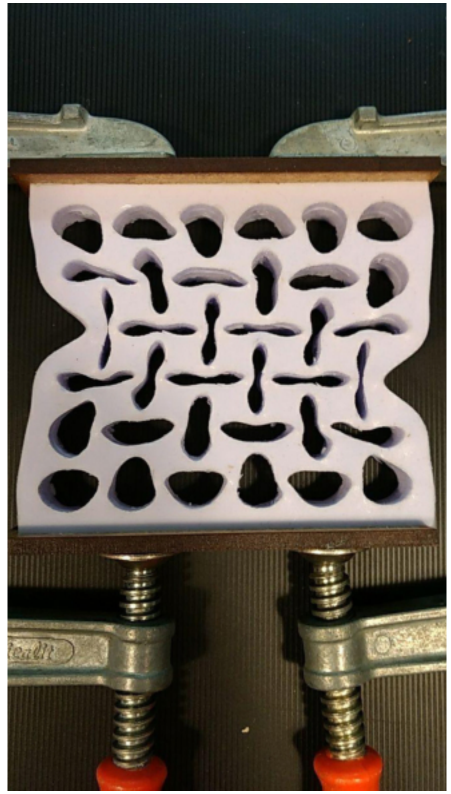
Experiment 3



test set-up

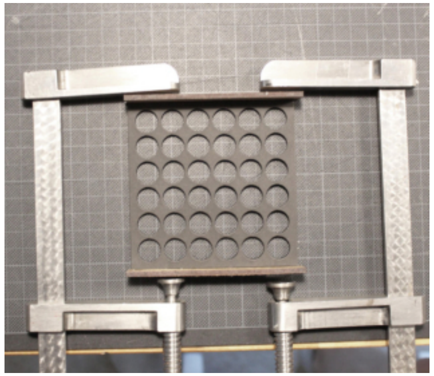
Following a combination of the instructions of Florijn et al. and Overvelde et al. also a soft matter metamaterial was created. For that reason, a mould made of MDF was lasercut. Four layers of 3 mm MDF cut in circular forms were stacked to create a mould of 12 mm height. 6 per 6 circles with a diameter of 13 mm and a spacing of 2.3 mm were arrayed to build a 100 per 100 mm specimen. This mould was grouted with silicone (Wagnersil 26 LE Premium Silikonkautschuk) with a high flexibility of XXXXXXXXXXXXX. After a period of 10 hours resting time to harden the mould was stripped off the piece and superfluous parts were cut out using a lancet.
The experiment conducted with the soft matter is a simple contraction experiment. In lack of any professional apparature to measure the force simply two clamps are used to compress the object. To apply the force uniformly to the specimen two washers of MDF are positioned on the two opposing sides of the prototype.

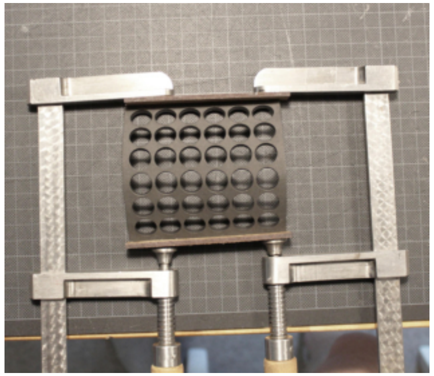



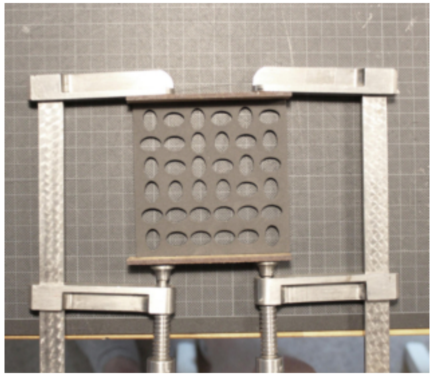
Results

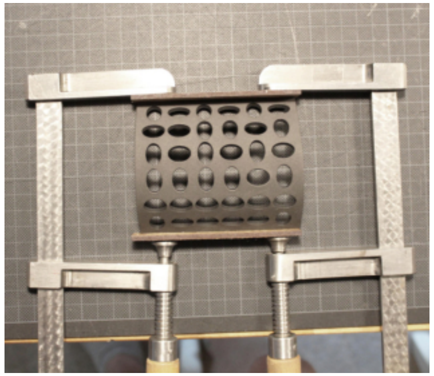
While casting the mold with liquid silicone it is important to fill in from a certain height of 15 cm or more to avoid blistering. Also it is vital to fill the mold only till to a certain point lower than the height of the stacked circles to avoid a consistent layer of hardened silicone like in figure XXX, that has to be cut out later by hand as to see in figure XXY.
Also, the mould should be designed tightly closed so that there is no chance the liquid silicone is leaking because it is quite fluid.
The results of the compression experiment of the specimen is resulting in exactely the expected movement according to the papers, although it is a movement that is not expected by any spectator to appear.

Experiment 4







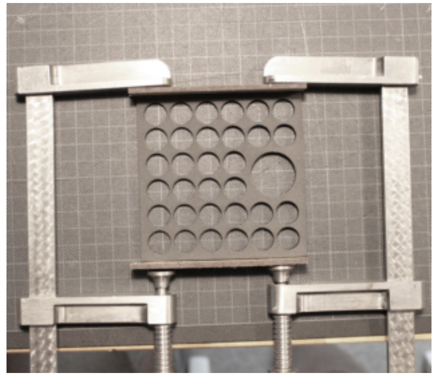


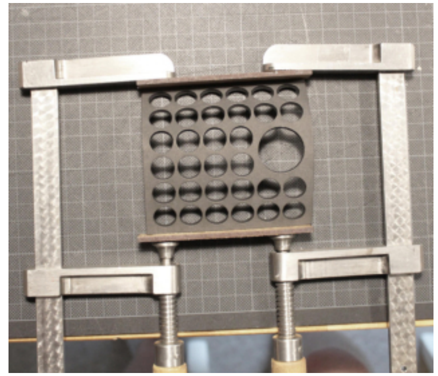
Test set-up

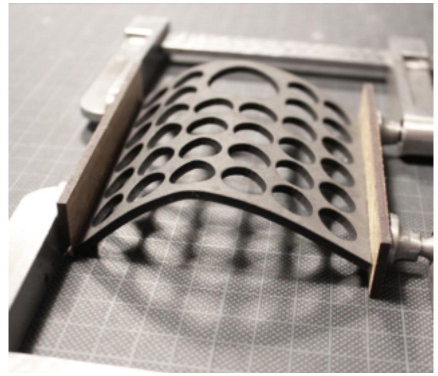
In addition to the experiments with rubber foam already conducted, the metamaterial structure of the soft matter is transfered to rubber foam as base material. A simple grid of circular cutouts and two more complex - also not periodic - structures are cut out of foam.
With these three metamaterials the same compression-test as for the soft matter is accomplished.

Results

It occurs in these experiments that these specimen do not react like the soft matter. Instead of the internal transformation of the structure simply the complete specimen







buckles in all of the three cases. (fig SSS,FFF;TTtD,DDDD)
This most probably is a effect of different ductility due to different Youngs-modulus of the materials. The rubber foam seems to have a lower Youngs-modulus than the silicone.
It is evident that different base materials are not equally good in forming metamaterials. Therefore, for each metamaterial structure a matching base matter can and has to be found.

In the following summary the tree materials tested (PLA, rubber foam and silicone) are summarised and their different applications for metamaterials are described.

3D-print

- best for real 3D metamaterials
- best if higher resolution printer
- more flexible material than PLA
- Youngs modulus of lower than 1,669 Mpa, rather 12 Mpa or 25 Mpa, ultimate elongation greater than 6%, rather 600%
- (Ninja Flex/Semi Flex)

foam

- best for rotating 2.5D metamaterial
- 3 mm rubber foam/neoprene
- Laser settings:
  15 % intensity, 0.8 or 1.0 speed
- 0.5 mm burnt cutline
- no rectangular edges
- minimal dimension to cut: 1.4 mm
- external bars min: 1.9 mm

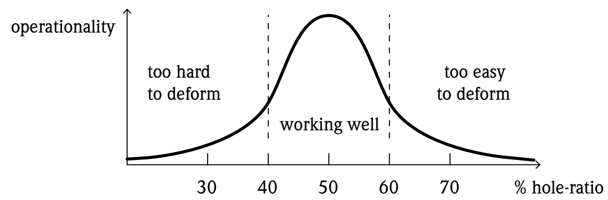
Discussion and summary

Given that these three different manufacturing methods with three distinct base materials all produce working metamaterials, it is shown that the metamaterials are mainly described by the structure that was generated.
But obviously, the original material influences the quality of the metamaterial.

The 3D-printed PLA is much more rigid and brittle than the rubber foam or the silicone, for example. This leads to lower performance in a deformation test. In effect, that lead to fracture of the specimen.
While the rubber foam is much more flexible, it also comes with the risk of bending of the bars. But, in contrast to PLA, that does not lead to fracture, but to a reversible buckling. Likewise, it is the most rapid manufacturing method of the three tested ones. Although, as shown before, it comes with the risk of buckling of the whole specimen ortogonally to the desired deformation direction.
The silicone is the most flexible of the materials. Thus, it is ideal to create a metamaterial. However, it is has to undergo the most complicated manufacture procedure of the three methods. Though, with its protocol containing a mould, it is possible to produce several of equal specimen after the first manufacturing effort.

silicone

- best for bending/buckling 2.5D metamaterial
- Wagnersil 26 LE Premium with Shore hardness: 26-28 Shore A ultimate elongation: 500%
- mould of MDF/plastic or styrofoam
- mould tightly closed
- infill with thin spurt to avoid blistering
- even parts smaller than 1.5 mm castable (silicone very flexible)
- hole-ratio: 63% probably too great, 55% easy to deform, 52% good, 47% works well, 32% too less (see graph YYYYYYY)
- better to cut off the margins to have consistent deformation



Summarising, all of the three base materials can be used for different purposes.

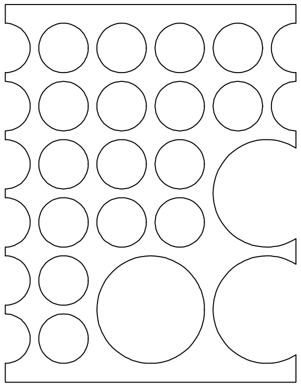
The 3D-printing process would be improveable with a different filament. Then it would be ideal to create 3-dimensional test pieces that differ in height. Tested were only 2,5-dimensional prototypes defined by only extruding a 2-dimensional geometry.

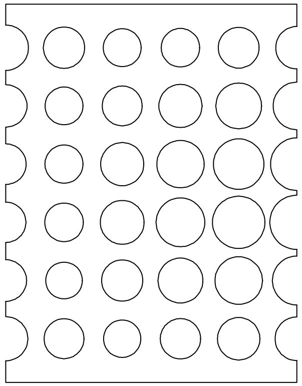
The rubber foam instead is not suitable for real 3-dimensional structures. It is the perfect method to produce the 2,5-dimensional specimen that have to rotate like the four-hinge. However, it does not produce sufficient results for metamaterials contracting on introduced compression.

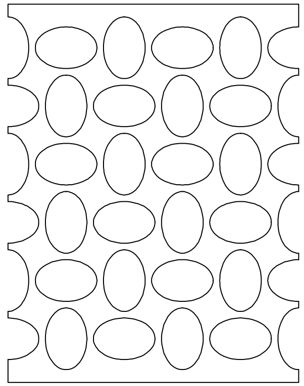
The silicone is perfect for these contracting metamaterials due to its high flexibility. Though, it would be too much effort to build a four-hinge that is simply rotating out of silicone because of the elaborate manufacturing process.

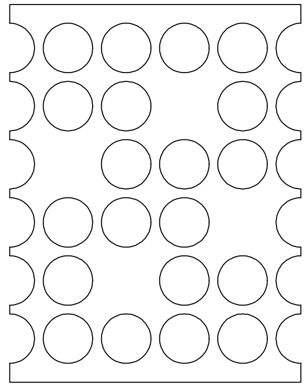
Altogether, by use of all these different manufacturing methods it could be shown that the metamaterial obtains new properties over the matter used to produce it.

Part 2 – Experiment 5







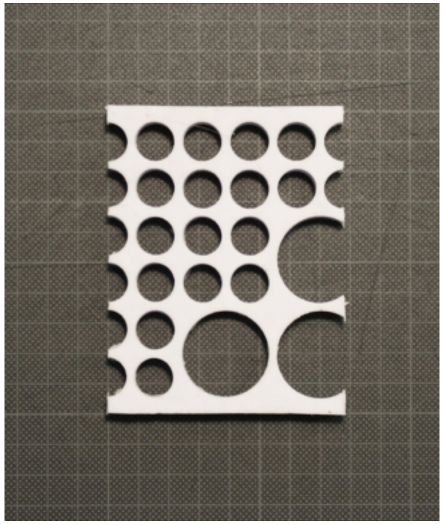


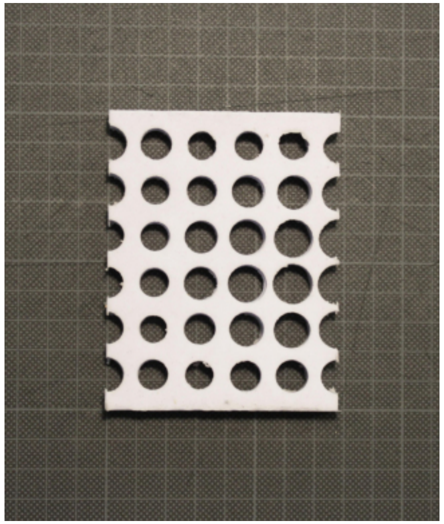
Set-up

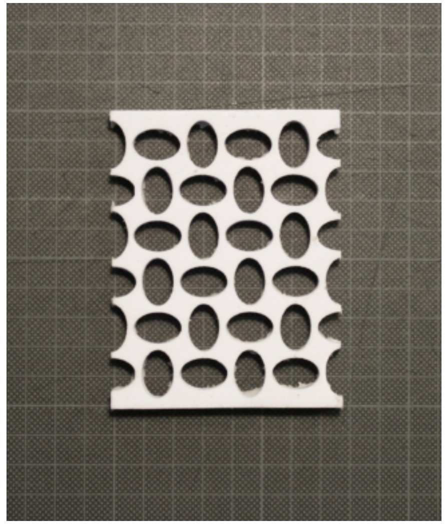
Now, after examining different methods to fabricate metamaterials, the soft matter metamaterial is modified to study the impact of different changes to the structure. Among these changes are different sizes and shaped holes 'defects' in the periodic structure.

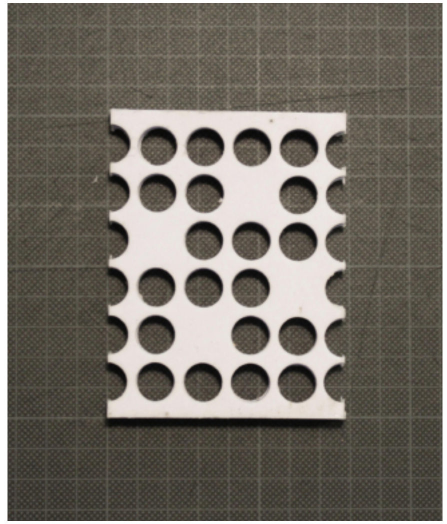
In figure XXX to VVV CAD-drawings of the new specimen are shown.
In specimen 1 and 2 the hole sizes are modified. While in specimen 1 there are two different sizes – one that builds the base grid, the other one that is a lot larger – in prototype 2 the hole sizes are differentiated gradually based on distance to a shaped curve through the material.
In specimen 3 the hole shapes are modified within a periodic array. The hole shapes are designed as ellipses and every other one is rotated rectangularly. Thereby, it results in the structure of a slightly compressed metamaterial already in the unstressed stage.
Specimen 4 is defined by 'defects' in the periodic structure. Four of the holes are left out to examine the material reaction under pressure to these stiffer areas. It is expected to lead to a directed deformation in the prototype.

The four new specimen are also varied in terms of their overall dimensions. Instead of having four outer walls only the upper and the lower one are kept. The other two outer boundaries are cut off, respectively not casted in silicone. This change reduces the amount of silicone needed and increases the flexibility of the prototype.
Also, there were no benefits of having four walls. The compression in each direction lead to the same deformation of the test piece.





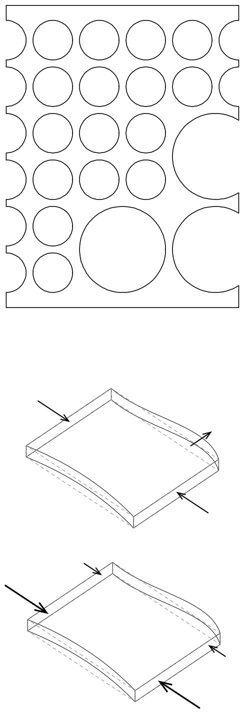


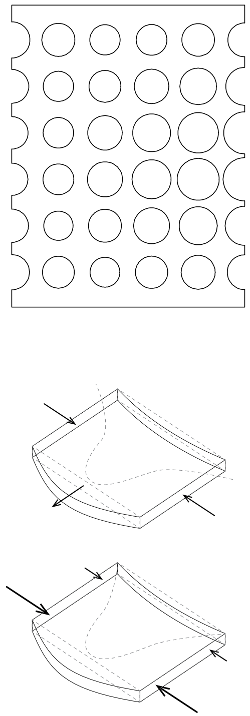


Results

The four specimen were built and casted like the specimen before. Differently the mould was designed with a height of 9 mm instead of 12 mm.
Two different adhesion methods were tested to glue the MDF parts together. With wood glue (Ponal express) the process was very slow while with spray glue it was much faster. Also, the result with spray glue could be improved. The initial adhesion was superior and the mould could be partly disassembled to set free the hardened specimen.
This time, it was made sure that the silicone did not spill over the mould. By that, the need to cut out the holes was avoided. Only a thin layer of silicone covered the MDF which could be rubbed off easily by hand.
Stripping the prototypes was quite easy, but in case of the third test object (figure VVV) the smaller parts (d = 1.7 mm) were harder to loosen. But, with the silicone being very flexible and durable it could be stripped completely. It could be imagined to create even thinner parts that are able to be cast and stripped.

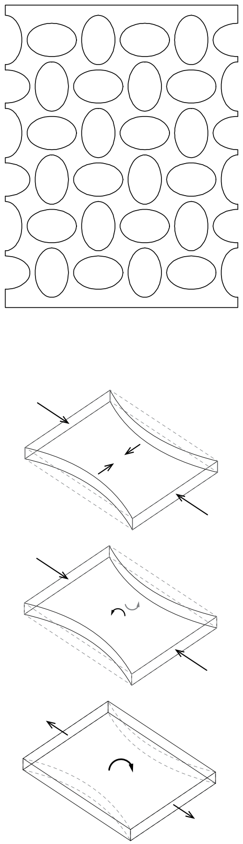
With all of the four specimen experiments were conducted.

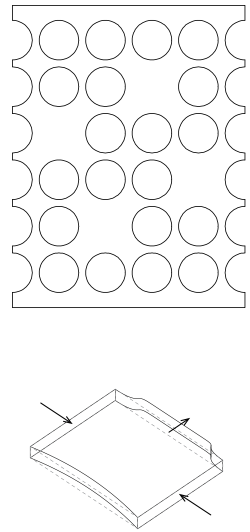


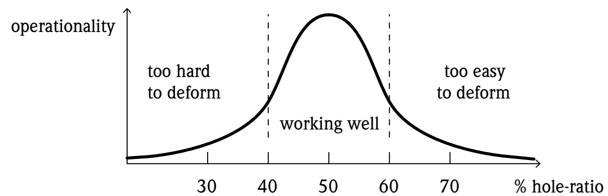


Discussion Overview

Summarising the four tested specimen, different force translations can be examined. While some parts always react ‘normally’ auxentic, some edges tend to bend out of this behaviour. The movements shown above summarize and visualise the findings of the experiments conducted.
While the compression is applied to specimen 1 and 2 the deformation and thereby the force is directed ortogonally to the sides. In one case in direction to the larger holes, in one case in direction to the smaller holes. This leads to the hypothesis of a operationality band that is diminishing to both sides (fig. SSSSS).
It is also to notice that it is easier to deform the specimen on one side, on the other side an increased force is needed.

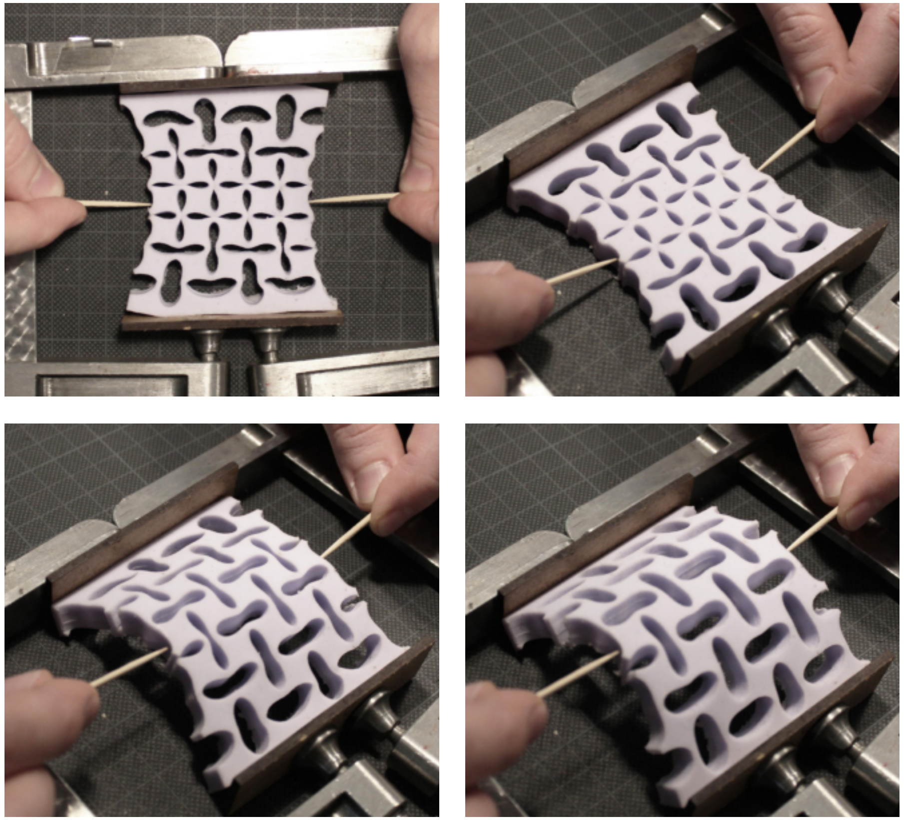






Specimen 3 has a periodic grid and buckles auxentically. While the force is applied it contracts perpendicularly. Within this movement, the grid cells rotate to an amount of 54° clockwise and anti-clockwise. This movement combination can also be invert-ed, thereas only to a smaller degree.
Specimen 4 has a deformation ortogonally to the compression that looks differently than the one in the previous specimen. The grid defects can influence the buckling behaviour. However, it is to mention that the control of this influence is hard to op-erate. Maybe the defects have to be combined with another change in the structure. On this, further research has to be carried out.

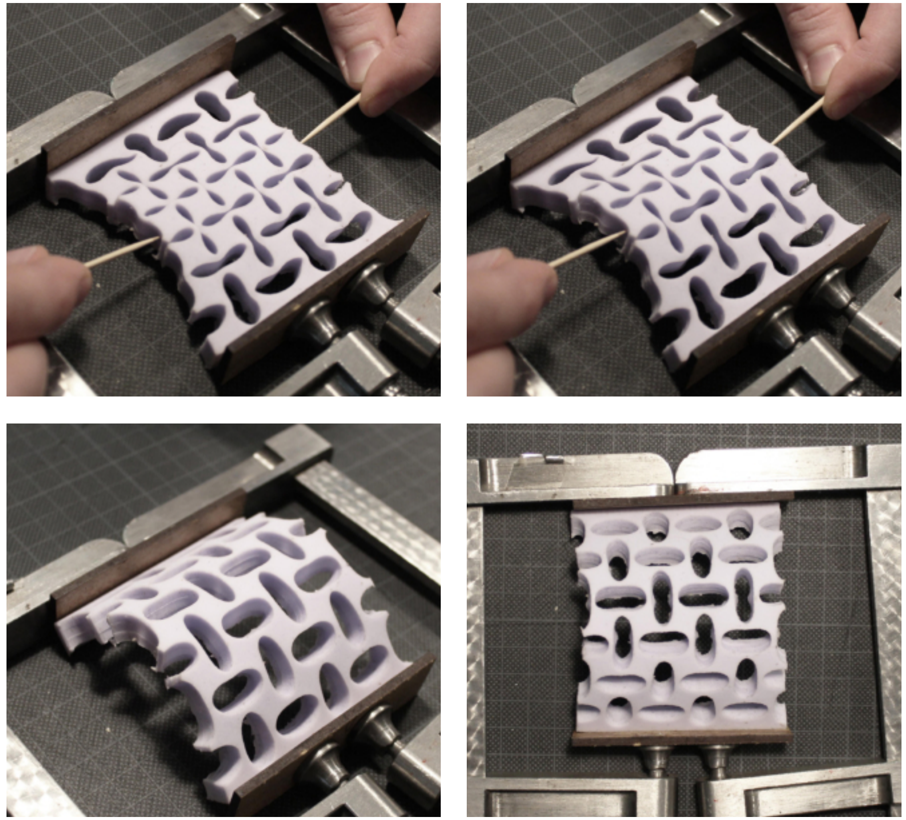
Part 2 – Experiment 6



Application idea

Finally, acidentally a new application for these metamaterials were found. By compressing the metamaterial and then applying a force perpendicular to the work-plane a pavillion-like structure can be build.
Combining the minimised dimensions of the compressed specimen with the self-enlarging structure it could be a interesting concept.
The result is quite stable and stands by itself.
It could also be formed customly by applying differently directed forces onto the barrel-shaped form. It is quite easy to shape.
For a lager scale though a stiffer base material instead of silicone would have to be chosen.

It could be used to create a pavillion. As well as a facade, shading device, roof or many different building parts.



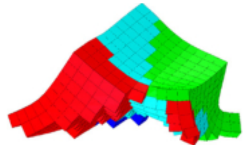
Application

The four different modifications of different hole sizes, gradient hole sizes, different hole shapes and grid 'defects' open up the possibility to direct movements and deformation within the metamaterial. By combining periodic and aperiodic structures different parts of the metamaterial could react differently to forces.
This varying reaction to forces or varying stiffness of flexibility could be used in soft robotics.[1,2] Within this domain, one soft robot could be build out of only one metamaterial not being forced to assemble parts.
Different applications could also be found in prosthetics and wearable tech.[3]
This very metamaterial examined in the research has auxentic material properties that can be varied by the modifications. These can be applied to shockers and buffers either in automotives or in parts of buildings. Maybe do develop a floor that reacts differently to movement than to falling objects.
The rotation happening in the material can be used for different purposes, as to create a locking system, a decorative element, a variable shading or a precise rotation. Especially when inverting the process a rotation can be turned into a useful linear movement.
At last the accidentally found 'pavillion' has to be mentioned.
Furthermore, the section of the metamaterial can be applied to facade, shading device, roof or many different building parts.

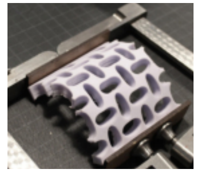
Future work

Firstly, all of the experiments conducted should be verified by proper measured tests in a laboratory environment.
In detail, as future work it is vital to investigate further the domain of 'defects'. Firstly, there are many possibilities to modify the metamaterial like this. Secondly, these 'defects' can also appear accidentally and unplanned in metamaterials that are produced in larger scale using atomatized fabrication processes. For this reason, it has to be known what the benefits, drawbacks and risks of these defects are.
Furthermore, the implementation of combinatorial design mentioned in Colais et al. has to considered to all of the metamaterials.
Also the now 2.5-dimensional metamaterials should be evolved to fully 3-dimensional structures.

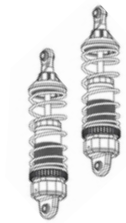
1 *https://www.youtube.com/watch?v=4ZqdvYrZ3ro (9.8.2017, 16:20)*
2 *https://www.youtube.com/watch?v=z9ptOeByLA4&spfreload=1 (7.8.2017, 15:00)*
3 *Coulais et al., "Combinatorial Design of Textured Mechanical Metamaterials," Nature (2016)*



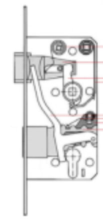
soft robotics http://www.creativemachineslab.com/soft-robot-evolution.html (10.8.2017, 12:30)



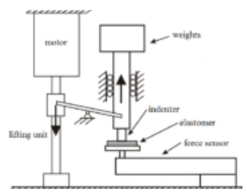
decorative, shading, packaging - pavillion, facade



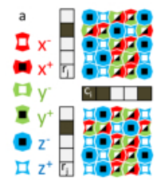
shocker/buffer - automotive or floor http://www.mz-modellbau-shop.de/WebRoot/ Sage/Shops/ MZ-Modellbau/52DE/ 6B21/DA63/ 116B/ 5787/ 0A0C/ 05DF/ A2BC/gsobild_491595.jpg (10.8.2017, 12:30)



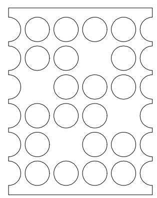
lock - translating force http://www.schluesseldienst-schuele.de/gallery/bestandteile-einsteckschloss-big.jpg (10.8.2017, 12:30)



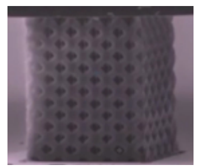
proper measured tests https://www.researchgate.net/profile/Lars_Voll/ publication/ 275517802/figure/fig1/ AS: 294573 0426183 68 @1447243094145/ Fig-1-Principle-sketch-of-the-apparatus -for-the-measurement-of-the-adhesive-force.png (10.8.2017, 13:00)



combinatoric computation



further investigation of grid 'defects'



real 3D structures