UNIVERSITY of WISCONSIN UWMILWAUKEE

3D Printing of Auxetic Concrete

Department of Civil & Environmental Engineering

Gabriel Stern, Aparna Deshmukh

Advisor: Dr. Konstantin Sobolev

Background

Auxetics are materials or structures that have a negative or neutral Poisson ratio [1]. This means that when a material is in tension, the cross-sectional area will increase and vice versa when the material is compressed. This occurs due to the internal structure of the materials or object, which is achieved by the chemical structure or cuts made into the material to create the structure. Auxetics can improve the mechanical properties by enhancing shear, indention resistance, damping, and fracture toughness. Due to these properties, auxetics could be applied to cement based composite structures to improve the life time and strength of the applications. Due to different needs and requirements of auxetic concrete, different structures and geometries will need to be made based on the criteria.

Making these structures will be difficult with conventional concrete manufacturing, requiring a different, more adaptable manufacturing: concrete 3D printing [2]. 3D printing of Concrete has been increasingly popular in the last decade due to its low production cost, potential material savings, reduced time saving, formless structures, and better-quality control. 3D printing of concrete would allow versatility which will be required in printing different structures. However, 3D printing of concrete has its disadvantages such as: a lack of printable cementous materials and mixes, limited methods of incorporating reinforcement into 3D printed structures, and the technology still being in its infancy.

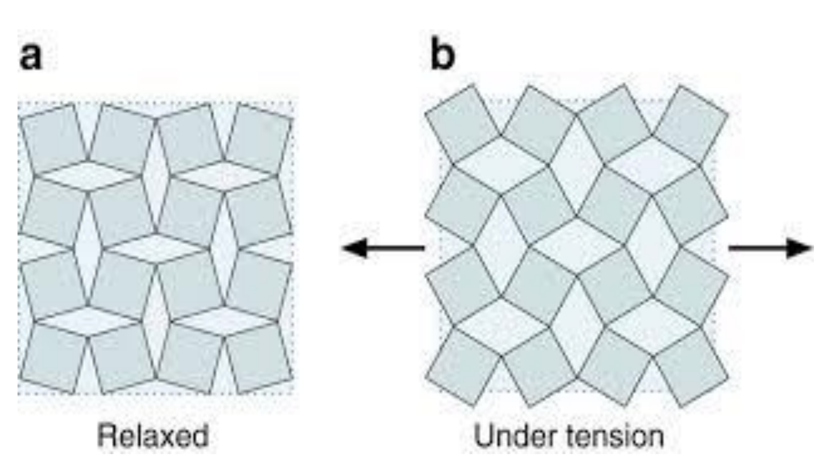

Figure 1 (left): An example of an auxetic structure. The diamond cuts in the material create a structure so that when it experiences tension, the structure expands creating a negative Poisson ratio. This structure is known as kirigami.

Approach

For concrete applications, the main focus will be on auxetic structures by creating a geometry made out of concrete that will have a negative or neutral Poisson ratio. Different auxetic geometries explored are: kirigami, origami, chirality and star systems.

Origami is often associated with folding paper into decorative shapes and figures. In engineering, origami has inspired new ideas and designs of engineering. Just like origami art, engineers use the concept of taking two dimensional objects that change into three dimensional structures, which can save space and weight in design. Some researchers have been working on origami structures that can fold and unfold through methods such as: thermal, chemical, and electromagnetic, without the use of external forces.

Kirigami (figure 1, [4]) is a variation of origami that uses an array of cuts, instead of folds in the materials to achieve the desired auxetic properties [3]. The cuts in the material can be modified to the criteria to give desired properties in deformation, stress, and more. Unlike origami, which takes a flat structure and makes it more compact, Kirigami takes something small and makes it larger. The cuts in the shape would also save material when produced.

Methodology

For research, it was decided to use kirigami due to its properties and function for 3D printed concrete structures. Before concrete kirigami samples could be created, a geometry had to be designed specific to the conditions the sample may experience. To do this, a part was created, simulated, and optimized using the finite element analyses (FEA) software, ANSYS [5].

The part created is a 13 x 9 cm sample with a thickness of 0.5 cm. A diamond shaped cut was then put into the sample with the dimensions entered as a parameter between two and zero cm. This cut was then patterned to create an array seen in kirigami and so all the cuts would be associated to the parameters of the original cut.

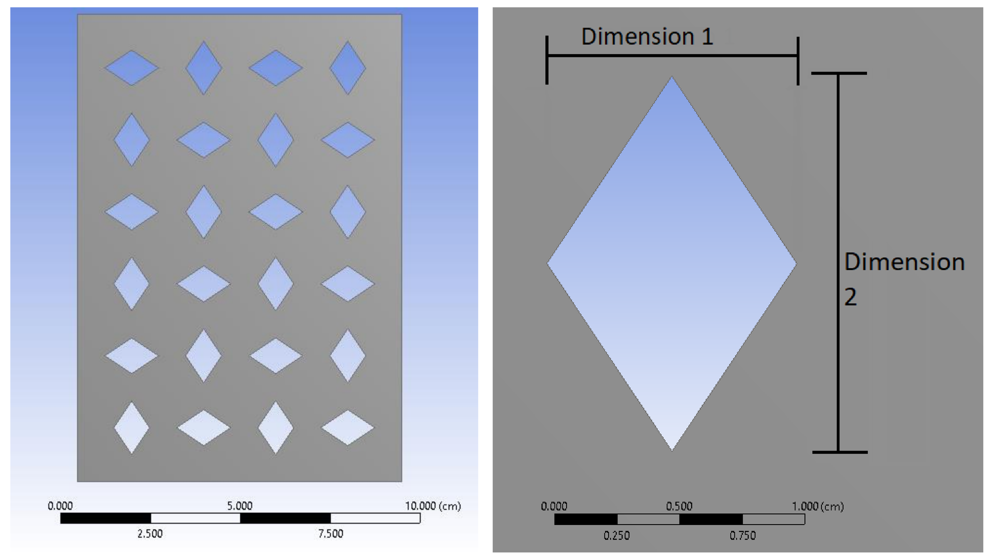

Figure 2 (left): The part created. A close up of the diamond shaped cuts show dimension 1 as the horizontal dimension and dimension 2 as the vertical dimension. The default values for dimensions 1 and 2 are 1 cam and 1.5 cm, respectively.

The part was then simulated using the "static structural" system which is a system used to determine displacements, stresses, etc. under loading conditions [6]. The bottom, short edge of the support was given a fixed support while the top, short edge was given an applied force of 20 Newtons, perpendicular to the sample. The part was assigned the default material properties of concrete. The output solutions from the simulation were total deformation, equivalent strain, and equivalent stress. From the results, maximum deformation, maximum stress, and maximum strain were parameterized for optimization.

After the design and simulation of the part, optimization could then take place. The analysis system used for optimization on ANSYS is called direct optimization. This system, uses the simulation outputs as objectives to maximize deformation, with minimum stress and strain. The system parameters used were the dimension parameters (dimension 1 and 2) of the part. What direct optimization does is take the dimensions and finds candidate dimensions that best meets the objectives given. Three optimization systems were created with different objectives for direct optimization: (1)minimize the maximum stress, (2)minimize the maximum strain, and (3) minimize the maximum stress and strain.

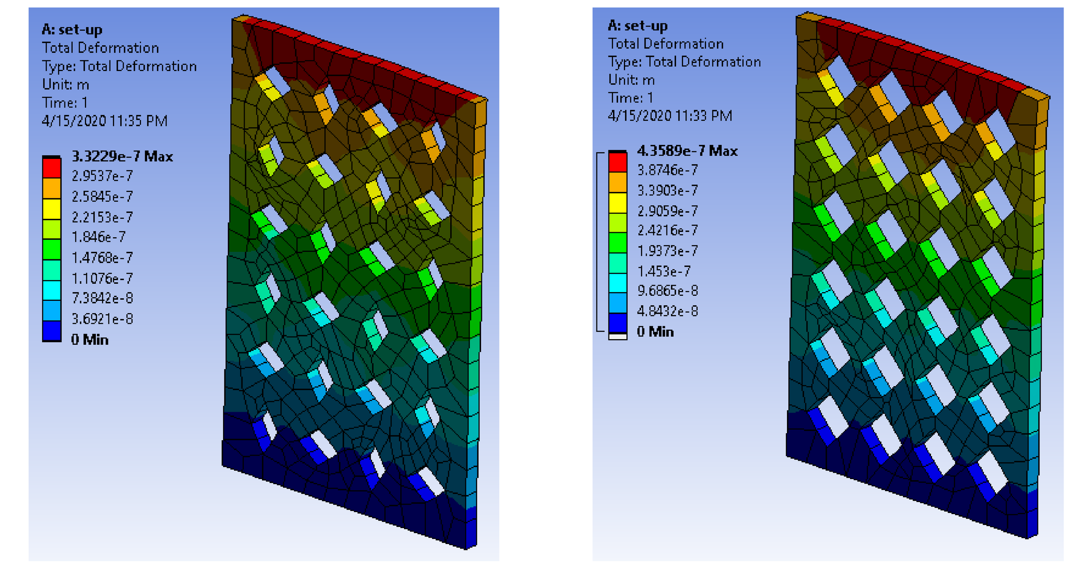

Figure 2 (above): The total deformation simulations of the part. The simulation on the right is prior to optimization and the simulation on the left is the part optimized to minimize the maximum stress and maximize the total deformation. With the optimized geometry, the part is able to deform more with an almost similar stress to that of the default geometry.

Results

The outputs of the three systems were three sets of candidate dimension set for each system (9 total candidate points), optimized to the objectives in the said systems. Each candidate point set also had a set of outputs of total deformation, maximum equivalent strain, and maximum equivalent stress. Using this data, one set of the candidate dimensions from each system (3 sets out of the 9 candidates) were selected that had the best results. These three sets of data were then compared with each other and the default dimensions prior to optimization, which is shown in figure 3. To clarify the charts, bars 1,2,3, and 4 are the data from the selected points from the default, minimization of maximum strain, minimization of maximum stress, and minimization of maximum stress and strain systems, respectively.

When the dimensions used were from the system where maximum strain was minimized (selected dimensions 2 on the charts), total deformation increased while strain and stress were approximately the same to the part prior to optimization (selected dimensions 1 on the chart). When the selected dimensions were used from the system where maximum stress was minimized (selected dimensions 3) deformation increased quite a bit compared to the other dimensions while stress and strain increased slightly more than the defaults. When the maximum stress and strain was minimized (selected dimensions 4), the total deformation, stress, and strain all decreased compared to the default data. This is most likely due to the system having an extra objective.

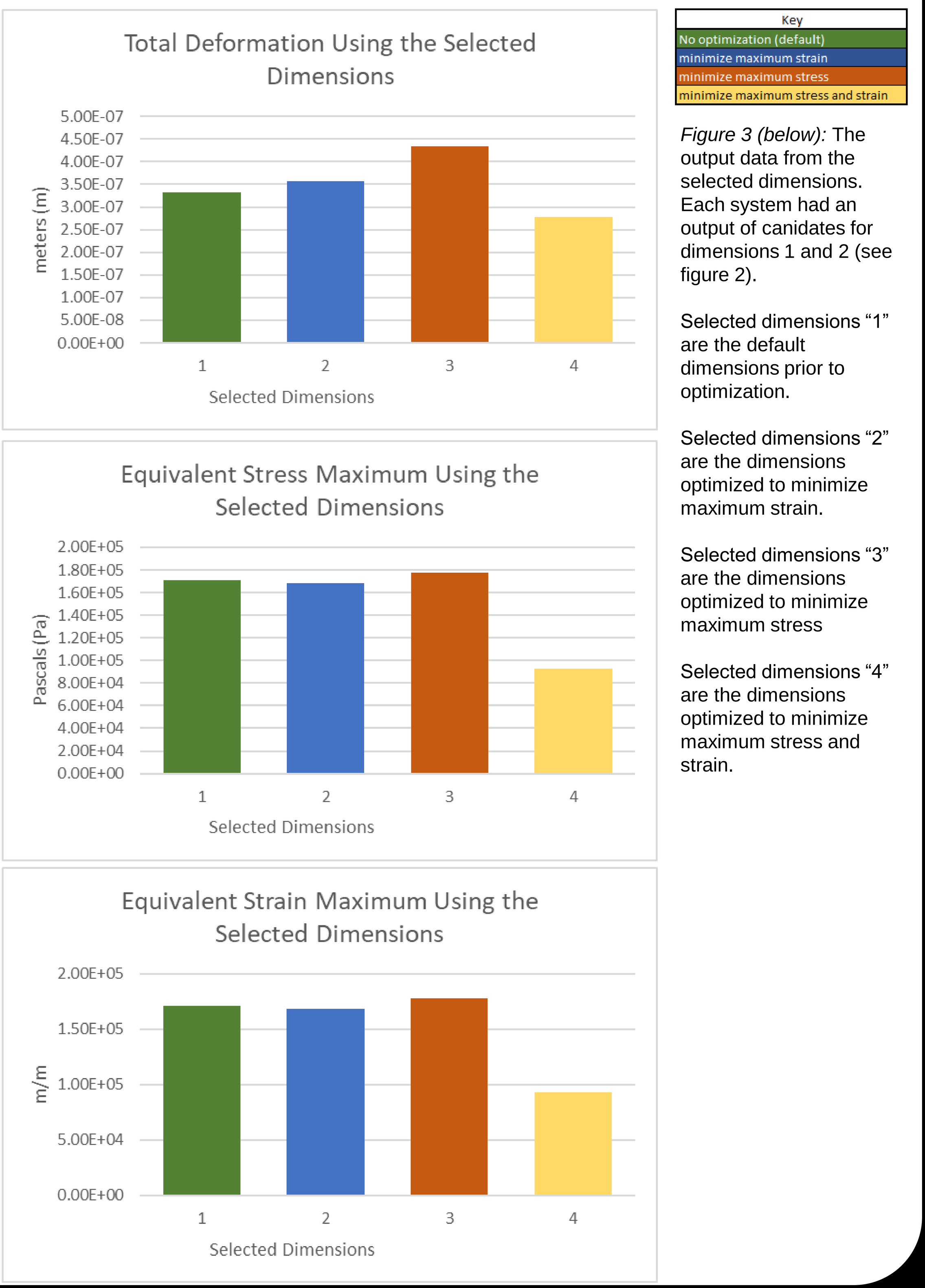

Figure 3 (below): The output data from the selected dimensions. Each system had an output of canidates for dimensions 1 and 2 (see figure 2).

Selected dimensions "1" are the default dimensions prior to optimization.

Selected dimensions "2" are the dimensions optimized to minimize maximum strain.

Selected dimensions "3" are the dimensions optimized to minimize maximum stress

Selected dimensions "4" are the dimensions optimized to minimize maximum stress and strain.

Conclusions

Auxetics are materials and structures that have a negative or neutral Poisson ratio which can change the properties of a material. Such properties include: enhancing shear, indention resistance, damping, and fracture toughness. Auxetics and its properties could be applied to cement-based structures toimprove capabilities and functionality of cement. The auxetics would be customized based on what the desired properties are, requiring a different method of manufacturing: 3D printing. As of now, 3D printing with concrete has its problems, but it would be ideal due to its versatility, time saving capabilities, and low production cost.

The approach used for auxetic concrete was kirigami, which uses an array of cuts in the material to achieve auxetic properties. Before creating concrete molds, a part was made with an array of diamond shaped cuts in computer aided design (CAD) software and then simulated using the static structural system in ANSYS. The properties simulated was total deformation, stress, and strain. To find a geometry that would have the most deformation with a minimal strain and/or stress, direct optimization was used. Direct optimization took the objectives of maximum deformation with a minimum strain and/or stress and modified the dimension of the diamond cuts that best met those objectives. Three systems were simulated with the overall objective to maximize deformation with the individual objectives of either minimizing stress, minimizing strain, or minimizing both stress and strain. Each system gave three sets of candidate points (dimensions) for the diamond cuts that the system thought best met the objectives.

These candidate points can then be further validated through simulation and physical tests to see if they can result in the desired auxetic properties. More geometries can also be tested where the array of cuts aren't associated to the same dimensions and instead have independent geometries. For these simulations, the material properties used, were that of the default concrete properties provided by ANSYS. Further research can use different materials, such as fiber imbedded concrete, that can improve the auxetic properties outlined. Auxetic concrete would open a whole new world in structures and 3D printing with concrete.

Bibliography

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