Analysing the Material Properties of Living Hinges

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Abstract

Additive manufacturing techniques have recently experienced a significant renaissance due to *Fused Deposition Modelling*, with cheaper and quicker generic 3D shape fabrication entering research and the market since 2010. Nonetheless, limitations exist with exponential material and temporal costs as size increases; thus, for simpler, larger, and lower-fidelity geometries, the much cheaper and quicker laser cutting is preferred, where intersecting planar slices approximate the volume and surface of the geometry.
This research expands on the concept of "living hinges", whereby patterns cut into planar sheets results in otherwise-rigid material becoming significantly deformable, by attempting to construct a computational model for predicting and controlling the properties of isotropic wooden sheets laser-cut with a spiral variant of living hinge pattern to achieve "double curvature" deformation behaviour. This would allow for the rapid fabrication of gridshell and tensile structures, which could replace less detailed yet more expensive surface structures of 3D geometries to significantly increase the efficiency of fabricating this geometry compared to pre-existing techniques.

Background

The current leading methods for realising 3D structures involve the layered application of plastic resins in processes generally called "3D printing". While these have the potential to realise nearly any arbitrary 3D structure, there are significant practical limitations, such as the exponential increase in material cost and construction time with increased structure size [1]. This has led to techniques that improve this efficiency by, e.g., hollowing the volumes and using internal support structures.
Another fabrication method involves the use of laser cutting to cut out 2D shapes from material planes. These 2D components can be connected together like a jigsaw to approximate 3D structures [2], with the main advantages being that the material cost is cheaper and the cutting process is much quicker.
Recent research has attempted to create a hybridisation of these techniques to exploit the advantages of both and thus lead to a general improvement in the realisation process. These generally focus on breaking down the given structure into a 3D printed shell (as 3D printing can better approximate details) and 2D laser cut internal scaffolds (as these approximate large structures more efficiently) [3]. Thus, in general, the more that can be laser cut, the more efficient processes can be.

Living Hinges

As laser cutting technologies have become more widespread, experimentation produced a variety of novel techniques. One of these is what's been called "living hinges". By laser cutting certain rectangular patterns out of the material sheets, the material exhibits flexible properties allowing it to be bended and folded through a given dimension beyond what would ordinarily be permitted without fracture by the material [4]. This original example shows a plastic sheet assuming the shape of a hardback book.

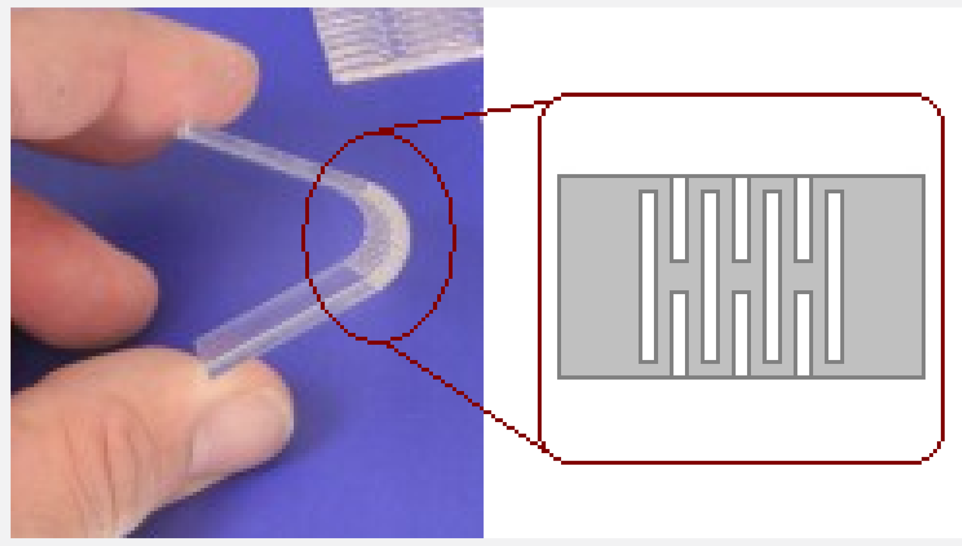

Figure 1: Lattice Living Hinges, by Solarbotics [4].

Spiral Pattern

A more promising class of living hinge employs a spiral pattern instead, with the result being that the material increases in flexibility in both dimensions of the sheet [5]. This two-dimensional flexibility gives rise to "double curvature", a property that would allow the 2D sheets to approximate surface manifolds of 3D space, and so has potential use in improving the efficiency of 3D structure realisation. While the creators of this technique give ideas as to the properties of this resulting structure, there is little quantitative data on how to predict or parametrise its material properties for use in modelling processes. This is the target of this research.

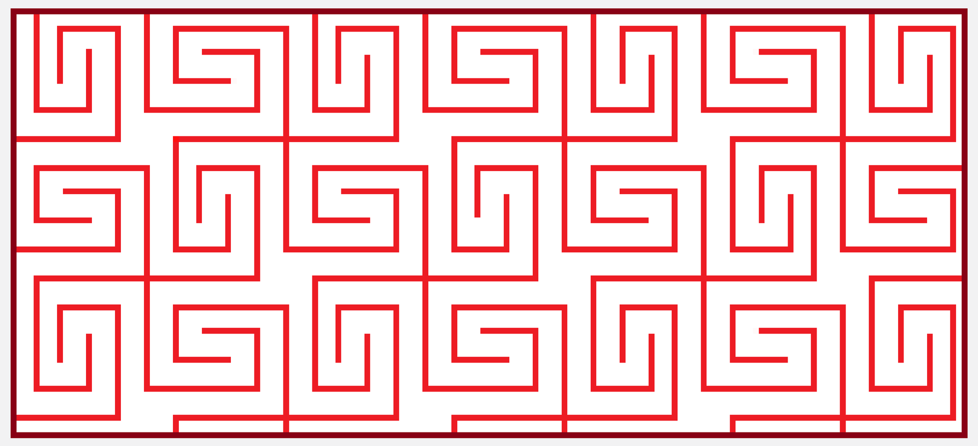

Figure 2: Template of the spiral pattern described above, with red lines showing the laser cutter path.

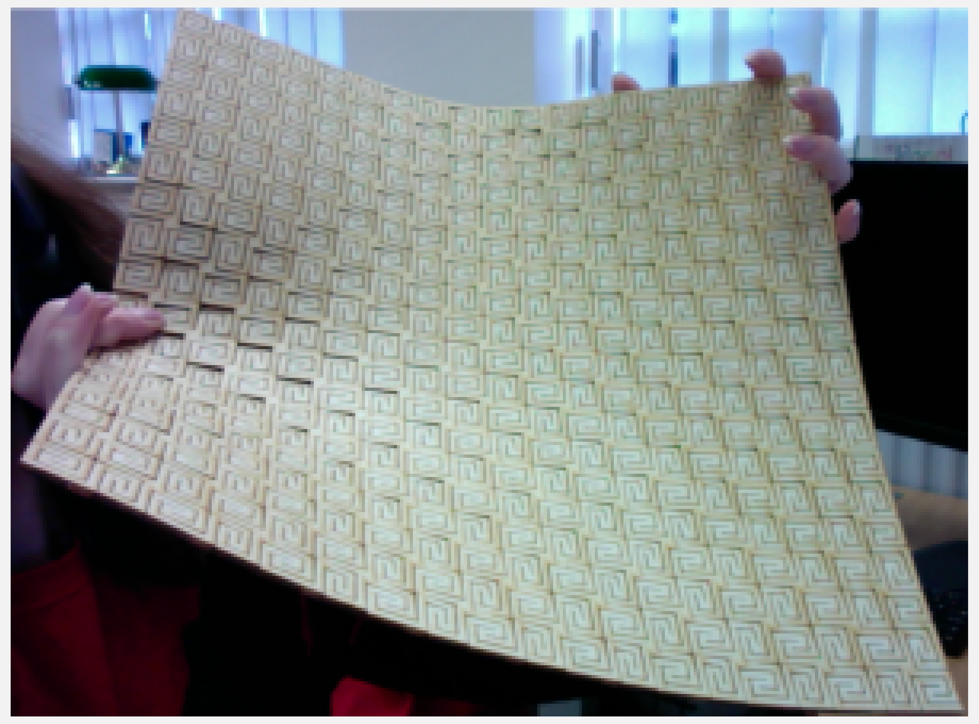

Figure 3: Double curvature demonstrated, with iconic "saddle-shape" topology showing local negative curvature with the positive curvature.

Methodology

In order to compute the properties of the material, begin with a simplified model representing the material. As a starting point, the situation can be envisioned as a uniform square sheet of material cut with a given metric of the spiral pattern and clamped at the corners and subjected to gravitational potential energy to see how it deforms. Additional forces can be added to determine an approximation of the structure's ultimate load.

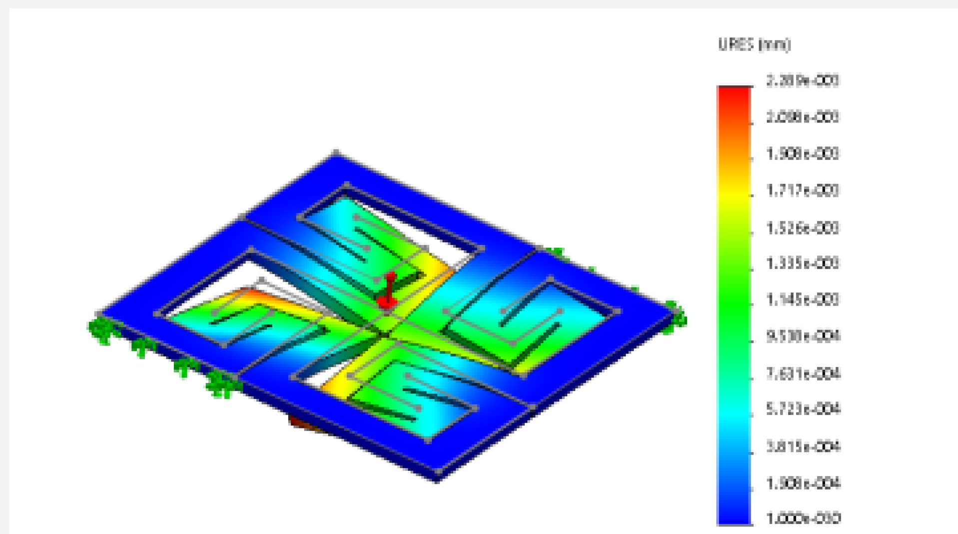

Figure 4: *SolidWorks* example showing displacement under gravity with clamps applied to external sides and corners.

This can be solved computationally as an optimisation of internal energy states: where all forces are balanced by the resulting internal forces of stresses is the resting state. By representing the structure as a subdivided mesh of interconnected rigid body quads connected at the vertices with boundary conditions set at the structure's corners to simulate positional clamping, this solution can be approximated using iterative numerical methods such as finite element analysis.

Each connecting vertex can be modelled as a spring, with resultant forces opposing the stretching and compressive forces applied to it, and the spring's physical properties such as Young's modulus being derived from the base material's properties.
This framework will then be compared against reality by testing varying metrics of the spiral pattern applied to varying sizes of the wooden material in the framework itself as variables applied to the system, and then in the lab, with the boundary conditions applied by means of a clamping mechanism, and the deformed displacements measured using an accurate measuring tool, such as a laser ranging device, calliper, or even a camera. MDF or another approximately isotropic material will be used due to difficulties simulating anisotropic grains in finite element methods.

Progress

Autodesk's *Simulation Mechanical* was initially used to provide finite element analysis out of the box and save having to reinvent the wheel, but varying limitations and instabilities resulted in this being abandoned. *SolidWorks Simulation* replaced this, and is currently used for the finite element analysis comparison, seen in the picture to the left. The above methodology is now being implemented as a plugin for *OpenFlipper*, a cross-platform open-source C++ framework for mesh processing which makes use of C++ plugins to perform mesh processing algorithms.
The experimental data remains to be obtained.

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