BENDING CURVATURE

A design tool for interactive complexity

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Abstract. Bending is a phenomenon that occurs with great frequency due to the presence of natural forces like gravity, wind. It occurs whenever an element is subjected to an external load applied perpendicularly to its longitudinal axis. Every known element, independently of its stiffness, exhibits certain amount of bending. This paper explores this phenomenon not as a failure mode to provide tolerance for, but as a tool to design with. The design research presented here emerged from a combination of digital explorations calibrated through analogue experiments of bending rods. The aim was to create a model that would incorporate the interaction between bending rods and the transfer of forces. Rods were connected to each other with rings that allowed for certain degree of freedom, though limiting them to be in contact with each other at all time. The rods started bending in various planes; their curvature is negotiated with that of their neighbours and thus a process of self-organisation with multiple parameters was present until equilibrium was attained. Intrigued by this observation, this research seeks to look at bending as a possible design tool. Understanding the behaviour of a single element in its simplex situation and simulating this behaviour in a computational environment has been the starting point for building up a model where complexity is built progressively as a result of local interactions among several bending rods.

Keywords. Bending; geometry; simulation; parametric design; optimisation.

1. Introduction
The research presented here explores bending as a design tool. It was initiated as part of a postgraduate academic agenda by the authors and has been
further developed ever since, including numerous experiments using a range of analogue and digital form-finding methods. This research looks into the aesthetical and structural aspects of a system that employs elastic bending as a method of prestress, creating structurally efficient assemblies for a variety of uses in lightweight architecture.

Though bending for architectural applications has been used since ancient times for the construction of huts and bridges (Dunkelberg 1985), the actual geometry of bending has not been studied in depth until very recently. The digital representation of a bending rod can be modeled using several different approaches approximating its form to a great extent. Architect Marten Nettelbladt has been experimenting with the geometry of bending and has created an important online resource of experiments and observations concluding that all ‘elastic deformation’ follow the same principals and therefore the same geometry (Nettelbladt 2008). A more recent development is the “Kangaroo” physics engine for interactive simulation, optimisation and form-finding within Grasshopper plug-in in Rhinoceros, developed by Daniel Piker; this can provide excellent results for the simulation of a single bending rod. This engine works in an iterative way calculating the interaction among predefined forces like springs, bending resistance, pressure and gravity, and their repercussion on the geometry, until a stable form is reached. As our research looks at bending as a design tool, the experiments conducted involved several interacting rods adding to the complexity of the system. The physical form-finding experiments revealed some unpredictable results that emerged from the self-organisational capacity of the system to regulate and distribute forces to reach equilibrium.

2. Form-finding experiments

The principles of construction utilised in our experiments have been extensively used in Bamboo structures. Frei Otto refers to them with the generic term “Curved Compression Rods” referring to arches, grid shells and other structures “whose form is determined by installing curved – and thus prestressed rods” (Dunkelberg 1985).

As part of this research two sets of analogue experiments were conducted. The first set employed material with thickness smaller than 1 mm, such as piano wires (Figure 1), focusing mainly on morphological and geometrical aspects, and the second set was conducted with GRP (Glass Reinforced Polymer) rods (Figure 2) that could also give an insight into structural issues, joints and forces; both sets aiming at understanding the behaviour of bending and the interaction among rods. Glass Reinforced Fibre is an anisotropic material with high Young modulus. When casted in form of a rod, the fibres are aligned along the length giving the material high elastic strength with flex-
ibility to bend. It also attains a high elastic limit thus allowing us to conduct experiments in cases that piano wires would get a permanent deformation.

![Figure 1. Form-finding experiments with interacting piano wires exploring bending and buckling in 4 different positions along the z axis.](image1)

![Figure 2. Loading tests with 9 mm GRP (glass reinforced polymer) rods with two fixed connections.](image2)

### 3. Observations on physical experiments

The above mentioned experiments aided us to formulate questions that would further push the research forward. Looking at a multiple rod system, it is really complex to understand the interaction between the curves, the geometrical aspect and factor that governs the extent of deviation. Through experiments with piano wires, we looked at aspects like torsional buckling and twist. One of the intentions was also to understand which are the stable positions of curves in terms of energy, though this was out of the realm of geometry and was not our primary aim. In the second set of experiments, curvatures were understood as being the governing factor for dynamics shown by the system. This was further tested by means of simple loading experiments. After a certain loading limit, the curve left its 2D plane in quest for a more stable position under those conditions (Figure 2).

In a system with multiple elements, the joints are actually points where the force is exerted. The amount of force depends on the value of curvature and the deviation is based upon the location of points with respect to the change of curvature. Therefore, by means of experiments this behaviour was tested and understood. Throughout the experiments, which started with single element, joints, and multiple elements and finally developing assemblies (Figure 3), curvature was observed and looked upon as a factor of interaction. It must be noted
that for experiments, force was applied to create displacement and its quantum is not relevant. Through a series of experiments, the behaviour of bending rods was catalogued in detail with the aim to understand and extract the parameters that control the geometry of interacting bending rods (Figure 4).

Figure 3. Model with multiple GRP (glass reinforced polymer) rods with fixed connections.

Figure 4. Diagram of parameters for GRP rod experiments.

4. Digital tools – A computational approach

Following the analogue form-finding experiments, a set of computational explorations aimed to further highlight the principles that affect the geometry of bending and the complex behaviour that arises from the interaction among bending rods. The physics algorithm employed here is partially based on a spring system with global and local parameters controlling each of the elements that are represented by lines and points. An environment is also defined to simulate the geometry. The algorithm is based on Stylianos Dritsas Physics engine published online in 2008.

The tool works on a geometrical model consisting of lines and points predefined by the user to achieve a particular behaviour. An inherited position
continuity is maintained and due to the connectivity, the resultant vector is also tangent continuously. Variable flexibility controlling the curvature capacity, length constrains, degree of freedom at ends and at junction, can be defined using local parameters and can be recalibrated after running the simulation to fine tune the form. By implementing certain pieces of code, analysis can be embedded during or after the simulation, thus offering opportunities such as mapping of trajectories, stress mapping, minimum volume enclosed among others and even generate a feedback loop system.

5. Experimental understanding of bending

The geometrical effect of bending has been studied through physical and digital experiments. Although these two approaches have been carried out separately, they have been informing each other in various phases. The first stage was a set of physical experiments that provided us with a detailed catalogue documenting the behaviour of the rods, alone, in small assemblies and under the influence of external forces. The digital approach is not a copy or a recreation of the same experiments in digital environment, it is an abstraction of the self-organisational principles of the rods and an attempt to simulate that behaviour with digital means. There are numerous factors that define the configurations obtained by the rods. Apart from the characteristics of the material (stiffness, rod diameter) the obtained geometry depends on their boundary conditions (position, degrees of freedom, tangency), the length of rods, the type of nodes among rods, the forces acting on the system (global, local). The manipulation of these parameters gave a number of different spatial configurations. The type of nodes selected and the geometrical configuration (curvature, direction and tangency of the rods) can enhance or constraint the load bearing capacity of the system. In the case of interacting rods, the configurations obtained are not a direct result that can be predicted before the experiment, they are rather an emergent result of the local interactions of forces acting on the rods.

The digital experiments employed springs simulating bending behaviour; various cases were studied, joining the springs alternately for continuity in the material, using truss logic to counteract torsion twists, experiments proved that the combination of springs acting under tension and compression proved to be the most efficient in simulating the rod behaviour.

Generally, physical experiments have explored the macro-behaviour of rods, while the digital experiments have focused on the micro-behaviour within one rod. These investigations aim at creating a design tool for interactive complexity; the understanding of the material constraints and the interaction of forces inform the design process of an architectural object or artefact.
6. Pedestrian bridge – a case study

The above research was further developed through a case study, utilising the findings and integrating them with additional architectural parameters for the design of Pedestrian Inhabitable Bridges - A Multi Responsive Form Finding Exploration (Figure 5), a design thesis written by architect Utssav Gupta as part of a post-professional degree in architectural research and design, at the Architectural Association in London. This project serves as a case study to test, analyse and develop an experimental algorithm that looks at bending as design tool through the use of simulations that constantly update a geometrically complex model through feedback loops.

Figure 5. Pedestrian Inhabitable Bridges over the river Thames by Utssav Gupta.

6.1. A TOOL FOR MULTI-PERFORMATIVE STRUCTURES

Bridges are transitional spaces and their design usually involves a large number of parameters. From a structural point of view stability and damping are key issues. Architectural and urban criteria on the other hand, require contextual integration. In this case, with London city acting as the site for intervention, the architect’s vision was a subtle design that would not disturb London’s skyline, a smooth flowing corridor connection between the areas around King’s college and South bank, over the river Thames. Since the river is navigable, there have been certain parameters ranging from port authority to river bed contouring that formed part of a set of design constrains. A multi branching system was deployed having different programs for each span responding to culture and context on each side. For a span with variable sections, each with different contextual conditions and responses, the algorithm finds a topology
that locally responds to constrains and yet maintains a global continuity and flow. It embeds structural principles to generate a viable solution.

Since the tangential continuity was a major concern in the topology, principles of continuity achieved in a bent structure were adopted, hence utilising the tools described in the first part of this paper. Through simulations and further development of the code, the aim was to create solutions for topology and path finding, form-finding and optimisation. For a multi-branching system with no particular convergence points and with different architectural program, each of the sections were unique and were required to be aligned keeping in mind the local curvatures, rise, loads, views, context, along with the overall calibration and smooth flow of branches in and out of each other.

Most of the key issues and their translations were found to be affecting each other, either by aiding or opposing certain parameters, for example, navigability required height clearance and a higher apex for structural stability, however from a pedestrian and urban point of view, a steep corridor was undesirable. Branching itself held a huge potential for achieving structural stability against self-load and wind load as well as in streamlining the path. Collating all these variables and embedding them into the previously discussed tool lead the simulation behaviour towards that of an optimisation code. Though many multi-variable optimisation theories have been debated upon, Thomas Weise’s paper on *Global Optimization Algorithms: Theory and Applications*, has more extensively outlined the nature of most existing phenomena. He has explained multi-variable optimisation simulations as a set of many local minima and maxima beyond which lies a global solution. The developed algorithm displayed a similar behaviour, it unfolds several times to jump over local peak until it attains a final range. It produced a family of solutions which when tested upon Finite Element Model, gave results that were further optimised. A comparison of the outputs shows minor differences in the stress levels, highlighting the optimal solution in a model that had slightly different branch lengths.

Once topological, path finding and trajectory were embedded, parameters for spatial definition vis-a-vis structure were also looked at. In some of the branches, depth plane varied from that of main span and got deeper with a simultaneous increase in stress levels. Cross sections were taken in later iterations of simulations that got optimised further with structure and path flow. In a post-process exercise using a separate code, morphology and surface geometry was developed over the base skeletal grid formation (Figure 6).
As a base algorithm, the code possesses a huge potential to host a plug-in that would perform various tasks and provide data to the main process. Some analytical tools have already been discussed above, but with further form generation aids, it would be possible to develop morphologies adapting to various environmental conditions. Prospects of such a powerful tool are open and its applications could also be versatile.

7. Conclusions and Future Research

This paper reports on an ongoing research, presenting for the first time some initial results and setting the frame for future development. Throughout this research physical experiments have always informed digital explorations to ensure the quality of the simulations. An interactive design tool is currently under development by the authors, aiming at producing novel design solutions that will utilise the stored energy in elastic bending to give rise to lightweight structures that are both elegant and structurally efficient, taking into consideration material characteristics and force-flow already during the initial design stages. The case study achieved to highlight the advantages and limitations of this new tool for a design task of complex programmatic requirements. The algorithm’s great potential lies in the fact that it can cater for multiple parameters at the same time. In this case, the bridge project apart from the structural issues also needed to respond to rise over the river for navigability, path alignment, curvatures for slenderness, and branching; each of which are interconnected and affect each other.
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References


