KERF BENDING: A GENEALOGY OF CUTTING PATTERNS FOR SINGLE AND DOUBLE CURVATURE

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ABSTRACT

The paper presents an ongoing research on kerf bending of sheet timber material, by removing material at strategically located areas on the surface, to weaken the material locally rendering it bendable. Through a series of experiments the aim is to understand the reciprocal relationship between the cutting pattern and characteristics such as bending curvature, material resistance under load, among others. By understanding the factors that lead to an increased degree of single or double curvature, the aim is to optimize these patterns by redesigning, combining and scaling patterns, as well as changing the direction of pattern elements. All experiments are documented, forming a genealogy of patterns that are grouped by type and geometric properties. The conclusions highlight the advantages and limitations of each cutting pattern with regards to the geometry, while they discuss the possibilities for differentiated curvature through parametrically differentiated patterns.

Keywords: kerf bending; architectural geometry; digital fabrication; curvature; cutting patterns

Introduction

Digital manufacturing technologies are evolving and becoming more accessible and widespread. New material properties and new construction techniques are steadily replacing the industrial materials and conventional construction techniques, while new designers are promoting the experimental use of new materials and the innovative use of traditional materials, such as wood.

This research explores a particular wood bending technique, which is called kerf bending or kerfing. Kerf technique refers to the removal of material at strategically located areas on a wood surface, to weaken the material locally in order to bend it. This technique is applied to produce objects of different scales and functions, from product design to small-scale architectures. (Gillkvist et al., 2016; Mitov et al., 2019)

The main goal of this research is to analyze and understand the wood curving technique, to collect pattern examples for kerf bending, to generate new patterns, to classify the patterns according to their characteristics and to discuss architectural applications of this technique. This research aims to provide recommendations and guidelines for the implementation of kerf bending and to aid in the development of digital construction prototypes and experiments for architectural applications.

Research methodology

In this research a combination of two research methods and analysis was used. The research is divided into the study of precedents study, based on findings from existing bibliography and a variety of references from experimental architecture, which aimed at investigating the curvature of wood by modifying pattern motifs. This part focuses on information about the application of the technique of kerf bending and the characteristics that govern it, the cutting machines and the clarification of the geometrical terms, such as single and double curvature, ruled and developable surfaces. The reference study is complemented by a collection of examples of application of the kerf technique in architecture and a description of the construction process, since no information on the construction process has been found for all the architectural examples, the research involved visual analysis and categorization in order to reach conclusions. Based on the knowledge gained through bibliography, the research team undertook a number of material experiments, to obtain a better insight into the process and material behaviour. The first experiments are based on existing patterns designed by Aaron Porterfield, a researcher that pioneered wood bending through kerf technique (Porterfield, 2000; Porterfield, 2005). By changing variables, such as the distances between slots, the scale of the pattern, the directions of the elements that form the pattern, and converting the linear elements into curved or dotted lines, a variety of conclusions were drawn, that were useful for further developments of the application of the technique.

Construction of curved surfaces in architecture is a time consuming and difficult process. There are many ways to construct curved surfaces, but in most cases molds are required, which results expensive for individualized production of single elements. During the last decade, a series of bending methods have been developed based on mechanical properties of the material, such as kerf bending. (Mitov et al., 2019)

Kerf bending is used in a variety of materials such as wood, plexiglass and metal. The main focus of this research is how to apply this technique to wood. Kerf bending is used in new woodworking industries and is considered a simple and fast way of bending, since it doesn't require special equipment and complex manufacturing techniques, such as thermal or chemical elaboration. The kerfs can be a part of a design or can be covered with a thin-flexible surface, such as a tap, or with a wood filler. (Güzelci etc, 2016; Moholy-Nagy, 2012)

This technique has certain advantages and disadvantages:

Advantages of kerf bending:

- Allows the generation of single and double curvature surfaces
- Provides an easy and fast way of bending, without the need for special equipment, except from cutting machines
- Suggests a manufacturing process without making an impact on the environment, as molds are not required
- It is applicable for a variety of materials such as wood, plexiglass, metal
- A wide variety of shapes may be applied for the kerfs

Disadvantages of kerf bending:

- In order to stabilize the curvature of the wood structure, fasteners like screws need to be used, as opposed to other wood bending techniques where the structure remains in curved form without further procedures
- Limitations in construction. Kerf bending is not applicable for large scale components cause to reduced strength of material
- Kerf constructions are not recommended for exterior space because of weakening of the material due to weather conditions.

Use of Kerf Bending in Architecture

Through research on examples from the literature and reference material found online, it has been observed that this technique has been used in small-scale architectural constructions, such as installations and pavilions, only during the last decade, mainly due to the reduction in timber strength and the need for high precision cutting, which is evidently improving with the development of digital manufacturing machinery. The kerf cuts are those that facilitate the bending of the material but at the same time they reduce its structural properties. As a result, in architecture it is mostly found in interiors, as well as in smaller objects such as furniture, lamps, accessories, etc.

Regarding the support of certain predetermined curvature in larger-scale constructions, there are two methodological approaches. According to the first, supporting mechanisms are being used, which are usually designed for each construction separately (e.g. The Wooden Waves, Mamu Mani, 2015), while according to the other, the construction consists of smaller repetitive elements supporting each other (e.g. Kerf Pavilion, MIT, 2012).

Regarding the texture of the curved surface, sometimes the cutting lines of kerf bending are prominent, resulting in a characteristic texture and revealing the wood bending strategy (e.g. The Wooden Waves, Mamu Mani, 2015) and sometimes the timber plates are further processed, filling the cutting gaps with special materials and paints (e.g. Mitov et al., 2019), which gives a smooth finish and hides the bending strategy on the surface.

EXPERIMENTS

The aim of the experiments is to study the characteristics of each pattern such as bending degree and strength, classify them based on the above and therefore create a database for the kerf pattens and their characteristics aiding future decisions on selecting an appropriate pattern for each construction. The first experiments were based on the kerf bending study by Aaron Porterfield (Porterfield, 2000). Each specimen is evaluated with regards to its curvature, bending strength, stretching length and twisting capacity and the required laser cutting time for its production. All specimens are 10x10cm and all their measurements are presented in tables, so that the results can be compared across patterns.

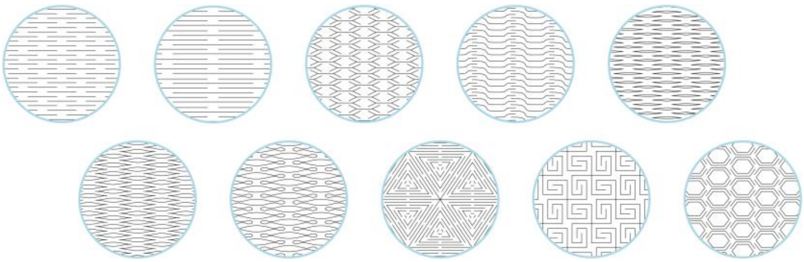


Figure. 2: Aaron Porterfield's Patterns

Calculations methodology

To measure the curvature (1/R) the specimens were photographed during maximum bending. In the photographs a curve was drawn approximating the curved shape of the specimen, and then through an algorithm the curve point with the maximum curvature was found and the curvature circle was drawn whose radius (R) was measured. Therefore, the curvature is measured based on the radius R of the circle. Double curvature specimens were measured by measuring the diagonal of the original specimen shape and the diagonal of the specimens at maximum bending.

Bending causes the specimens to deform or even break. To find the bending strength limit of the timber plates it was necessary to break them. By stabilizing the specimens and exerting a superficial force with weights to the limit of their fracture, a comparison was made between them, with weights ranging from 0,20 kg to 26,56 kg.

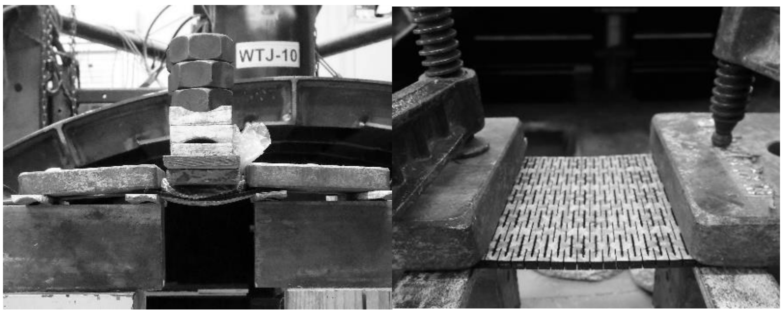


Figure. 3: Bending Strength Experiments

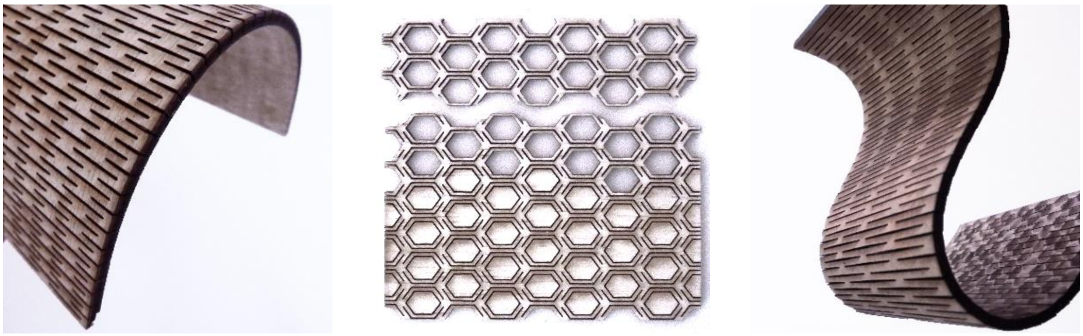
Some specimens during this process are elongated. This property is listed in the table as stretching length and was calculated by subtracting the original length of the specimens from the final length when stretched.

Some specimens had the ability to twist and create a ruled double curved surface. Patterns with this attribute are highlighted in the table.

To calculate the laser cutting time, a python script was used with the speed settings set to 25%. The laser cutting time was calculated algorithmically, because the timber plates were cut on three different laser cutters and if the actual time was measured the results would have not been comparable.

Experiments in different wood types

The type of wood is a very important factor in wood bending through kerfing technique. The first experiment involved cutting patterns on natural wood such as balsa and artificial wood such as plywood and MDF (Medium Density Fiberboard) to observe the differences in the characteristics of each wood. Regarding balsa wood, the specimens could not be evaluated properly, because balsa is a fragile material and the specimens were easily broken during bending. The plywood and MDF specimens were heavily curved. However, since MDF wood has been largely processed and is not governed by the characteristics of timber, the material selected for the subsequent study experiments is plywood.



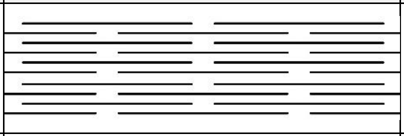
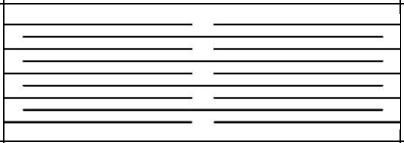
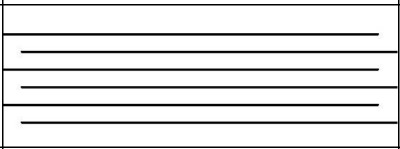
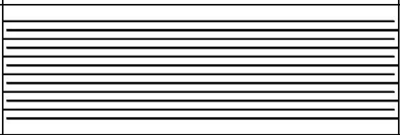
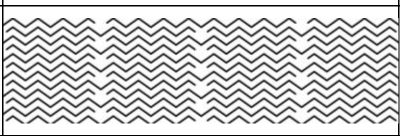
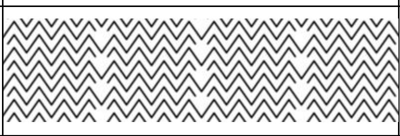
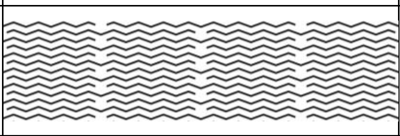
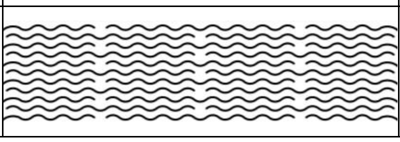
(a) (b) (c)

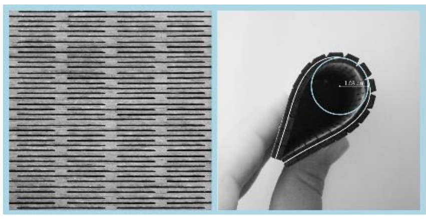
Figure. 4: (a) Plywood, (b) Balsa Wood and (c) MDF

Pattern experiments

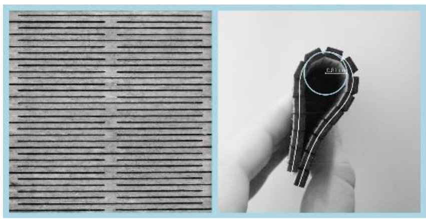
Linear patterns of parallel lines

Table 1: Properties and measurements of linear pattern kerf specimens

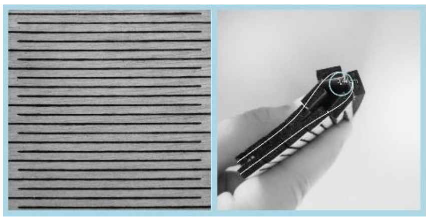
#	*Pattern*	*Curvature (1/R)*	*Double Curvature (cm)*	*Bending Strength (kg)*	*Stretching length (cm)*	*Twisting capacity*	*Laser Cutting Time*
1		*0,92*	*x*	*9,555*	*0,5*	*x*	*03:14*
2		*1,23*	*x*	*4,410*	*1,8*	✓	*02:32*
3		*2,27*	*x*	*1,940*	*4,5*	✓	*02:09*
4		*3,33*	*x*	*0,200*	*29*	✓	*04:11*
5		*1,42*	*x*	*1,940*	*3*	*x*	*04:40*
6		*0,59*	*x*	*1,830*	*1,6*	*x*	*04:40*
7		*1,03*	*x*	*2,080*	*2,2*	*x*	*04:46*
8		*1,03*	*x*	*3,700*	*2*	*x*	*04:08*



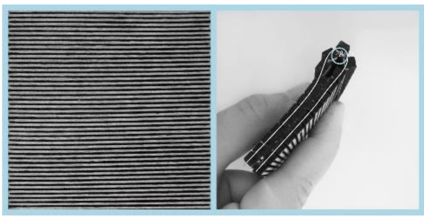
1. This pattern is designed by Aaron Porterfield and consists of horizontal parallel lines, which present discontinuity at two or three points. This is the most common pattern that has been applied to structures which use this bending method. It is observed that the specimen reaches a high degree of curvature and strength.



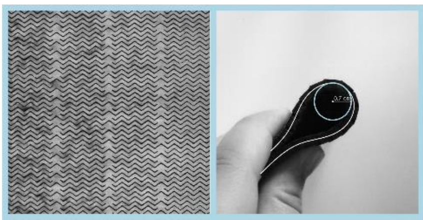
2. An inquiry that emerges from the above experiment is whether the discontinuity of the lines affects the curvature of the surface. So, a similar pattern was designed, with discontinuity at one or two points, instead of the two or three points of the original. The new pattern bends more, but its durability is affected because more material than the original is removed. The new pattern has more stretching capability.



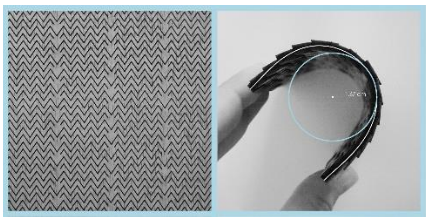
3. Subsequently, a pattern was designed consisting of parallel lines which present discontinuity at one point only, towards the boarders of the specimen right or left alternatively. The specimen reaches high bending degree and is distinguished by pliancy. In particular, when the pattern applied to 20x10cm timber plate, it can be twisted by 180^{o}.



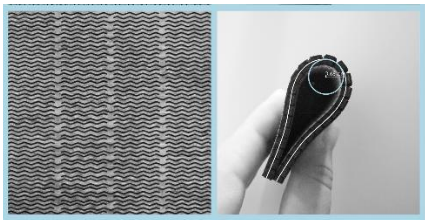
4. The same pattern, with a higher density of parallel lines, was designed. The distance between the lines was reduced from 4,4 mm to 2,2 mm. The bending degree, the pliancy and the twisting capacity are increased, compared to the previous specimen. However, this specimen appears to be brittle and faceted as the ratio between kerf lines and timber thickness is affected dramatically.



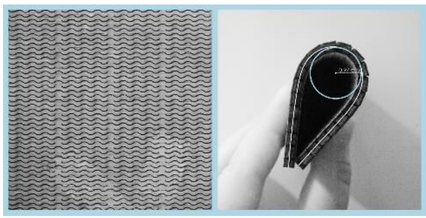
5. Based on the first linear pattern, a new pattern was designed where the straight lines were replaced by polygonal chains, with a spacing of 1,85 mm. The basic idea of the experiment was to create a single line, which would change direction and interrupt the continuity of the timber fibers in more places causing more curvature. The specimen is distinguished by pliancy. In addition, it is observed that exerting force at antisymmetric points results in twisting of the surface, creating a ruled double curved surface.



6. Subsequently, a question that arises from the above experiment is whether the angle of the polygonal chain elements affects the curvature of the surface. Therefore, a new pattern with acute angle elements is designed. The specimen is distinguished by flexibility and twisting capacity.



7. Meanwhile, a pattern with obtuse angle elements was designed. This specimen bends more than any of the above polygonal chain specimens, it exhibits greater strength and pliancy, but it is not capable of double curvature.



8. This pattern emerged from the original polygonal chain pattern by changing the curvature degree of the polyline. The specimen attains a lower degree of curvature than the original, but it is distinguished by more durability and flexibility.

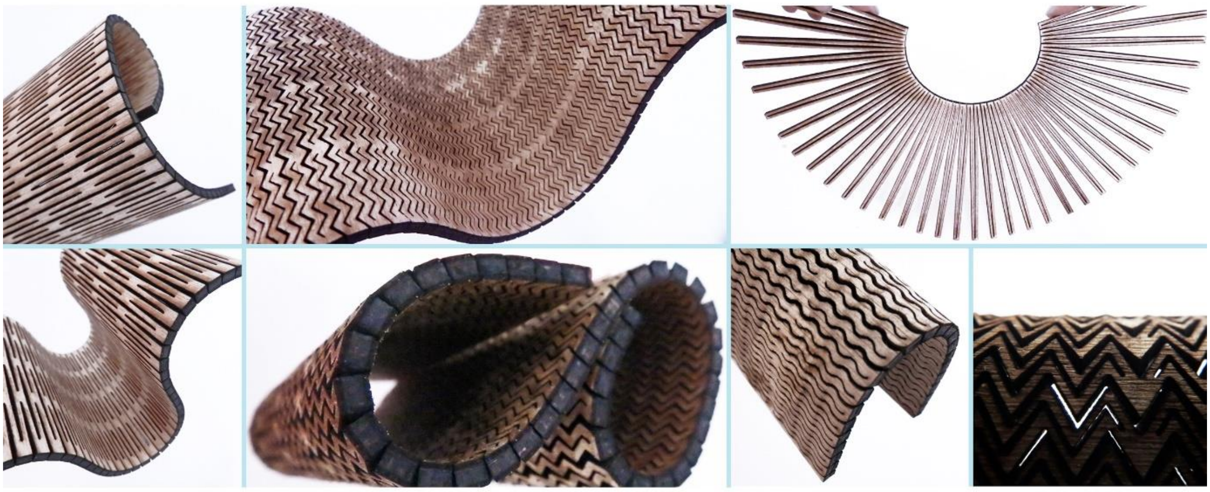


Figure. 5: Specimens of Linear Patterns

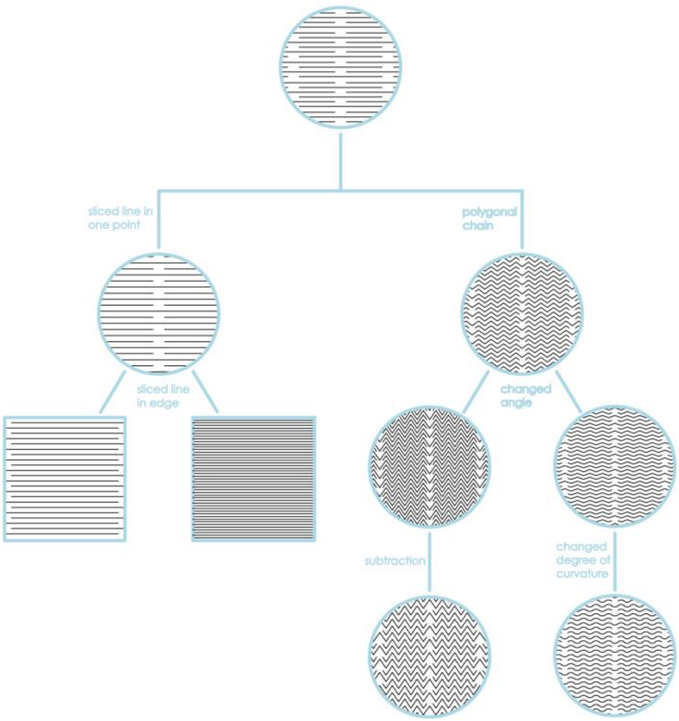
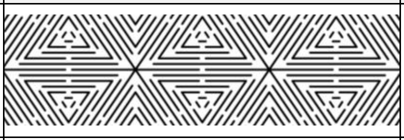
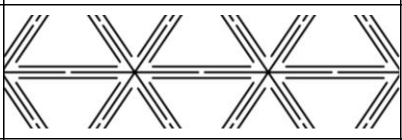
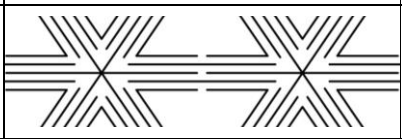
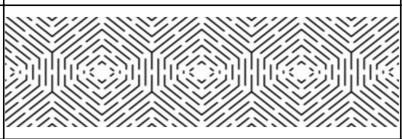
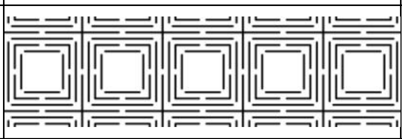
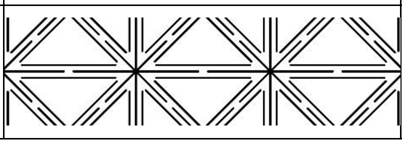
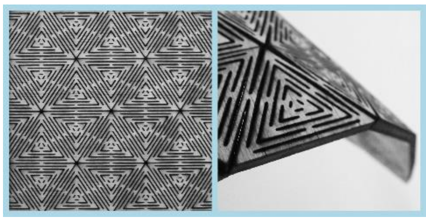


Figure. 6: Genealogy of Linear Patterns

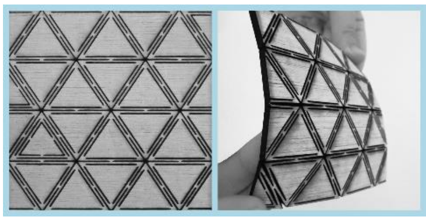
Offset patterns

Table 2: Properties and measurements of offset pattern kerf specimens

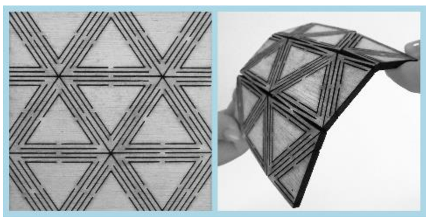
#	Pattern	Curvature (1/R)	Double Curvature (cm)	Bending Strength (kg)	Stretching length (cm)	Twisting capacity	Laser Cutting Time
9		-	*3,5*	*5,125*	*x*	✓	*05:13*
10		-	*3,5*	*19,055*	*x*	✓	*02:37*
11		-	*3,8*	*12,110*	*x*	✓	*02:55*
12		-	*0,7*	*9,245*	*x*	✓	*04:42*
13		*5,29*	✓	*18,515*	*x*	*x*	*04:33*
14		-	*2,9*	*14,105*	*x*	✓	*03:43*



9. This pattern was designed by Aaron Porterfield and comprises of equilateral triangles with offsets of equal spacing. The pattern is distinguished by high durability and double curvature capability. The points where the lines present discontinuity are more strained during bending of the specimen and are considered as fracture points. The points that the triangles intersect, are the points of maximum curvature of the specimen, they are points of intersection of six lines and they act as a hinge connecting six flat triangles.

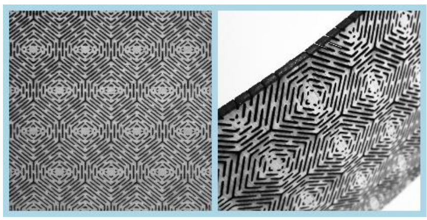


10. During the bending process of the previous specimen, it was observed that the pattern was affected only by the first and second series of the triangle offsets, and not by the following ones. Therefore, a new pattern emerged, which consists of the first two rows of the triangle offsets. Eventually, the experiment proved that the specimens reach the same degree of curvature, but the new pattern greatly increases its durability.

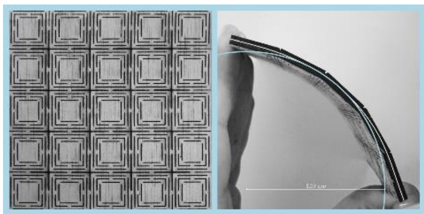


11. Subsequently, the pattern was designed on a larger scale. The basic idea of this experiment was that by increasing the length of the lines towards the points of maximum curvature, the surface would achieve a bigger curvature. The experiment shows that the specimen reaches a higher curvature degree than the original.

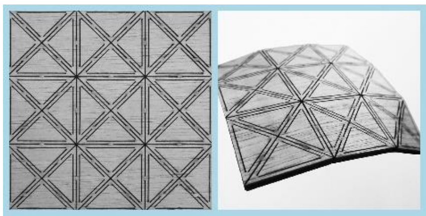
This double curvature pattern reaches a high curvature degree, independently of factors such as plasticity and durability. For this reason, patterns based on the same design principles but with other shapes were designed. The first shape chosen for study was the hexagon.



12. This pattern consists of hexagons which contain five offsets of them with equal spacing. Since this was the first attempt of redesigning the pattern shape, it was chosen to add all the hexagon offsets, to observe the reaction of the pattern. The experiment did not have the expected results. The pattern lines in different directions create double curvature, but the pattern bends only slightly. The curvature is affected, as in the previous experiment, by the first and second offset rows, so the rest can easily omitted.



13. The design of a new pattern with squares, based on previous experiments displays a different behaviour, it is observed that this timber plate bends in two axes (x and y), due to the symmetry of the pattern. Moreover, there is only very limited double curvature.



14. From the previous experiments it is deduced that the surface reaches its maximum curvature in the area where most intersecting lines are found. For this reason, a pattern with eight interesecting lines was designed, as opposed to the first pattern with six intersecting lines. The bigger the amount of intersecting lines, the bigger curvature degree will be achieved. The number of interesecting lines impact the number and the dimensions of the triangles. As a result, this specimen is bending less than the first, because of the smaller length of the lines.

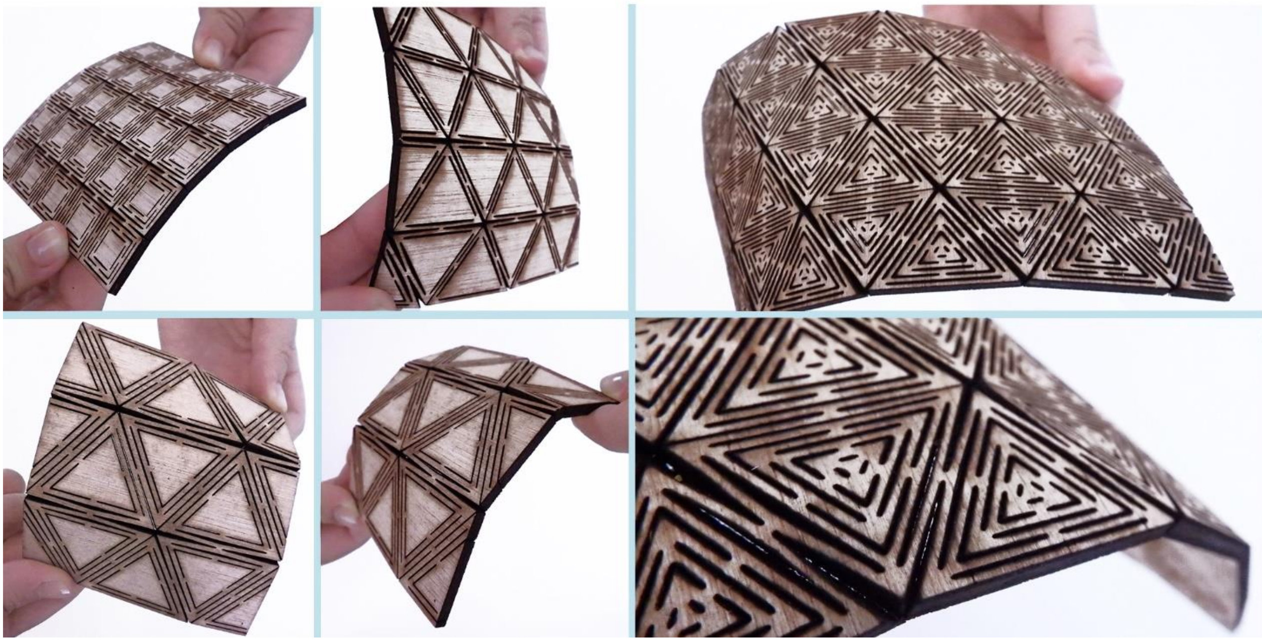


Figure. 7: Specimens of Offset Patterns

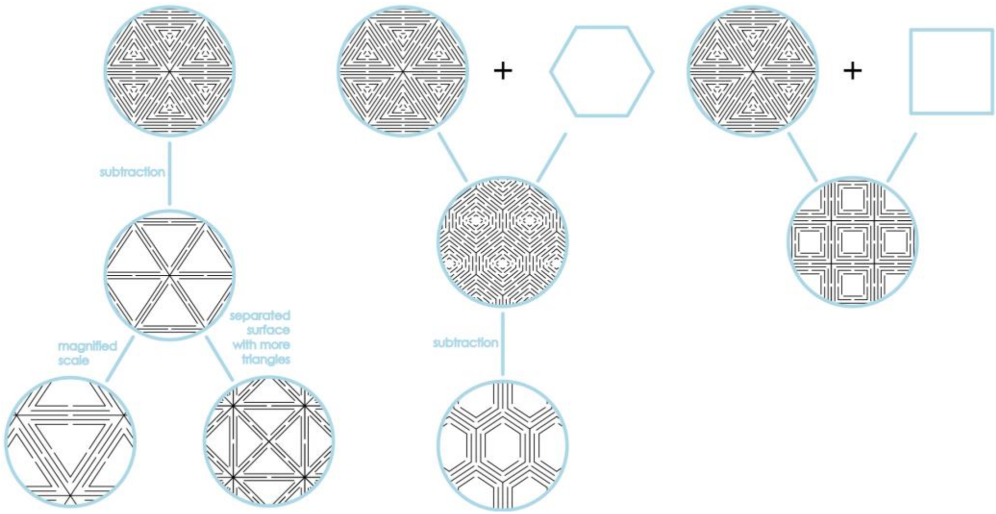
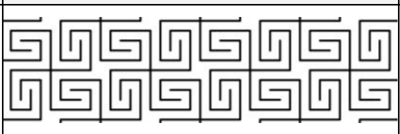
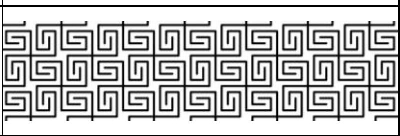
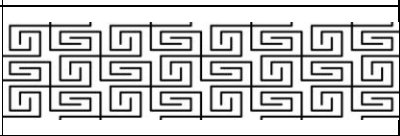
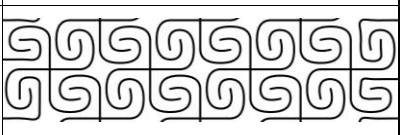
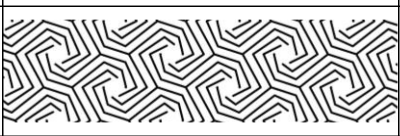
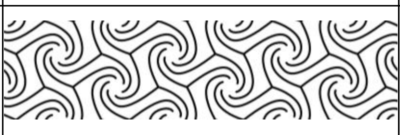
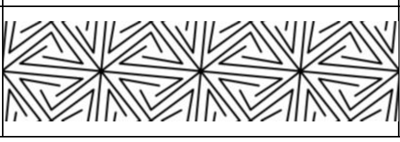
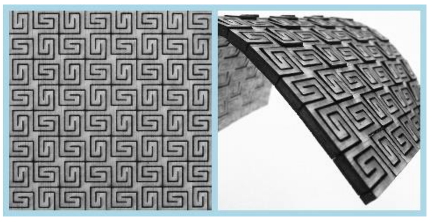


Figure. 8: Genealogy of Offset Patterns

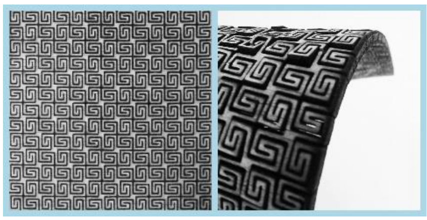
Meander patterns

Table 3: Properties and measurements of meander pattern kerf specimens

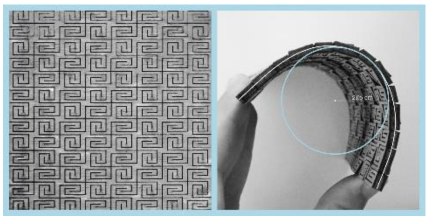
#	*Pattern*	*Curvature (1/R)*	*Double Curvature (cm)*	*Bending Strength (kg)*	*Stretching length (cm)*	*Twisting capacity*	*Laser Cutting Time*
15		-	*3,9*	*12,155*	*x*	✓	*03:32*
16		-	*8,2*	*9,755*	*x*	✓	*05:37*
17		*0,48*	*x*	*9,230*	*x*	✓	*04:35*
18		-	*2,4*	*11,210*	*x*	✓	*03:20*
19		-	*4,4*	*9,560*	*x*	✓	*04:35*
20		-	*1,3*	*21,330*	*x*	✓	*03:46*
21		-	*3,2*	*7,220*	*x*	✓	*04:23*



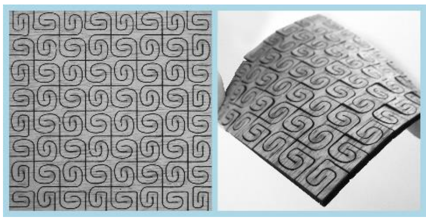
15. This first meander specimen is flexible and durable. The double curvature of this pattern is based on the long length of lines and the change of their orientation.



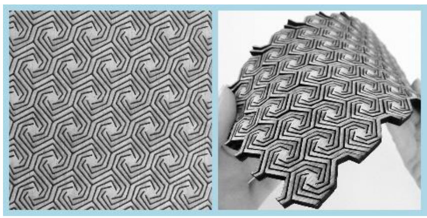
16. After conducting an experiment at a smaller scale, it emerges that as the scale of the pattern is reduced, the specimen becomes more bendable and less durable.



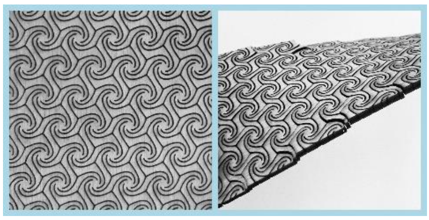
17. After scaling the original pattern in one direction, a different pattern emerged which does not display double curvature resulting in a single curvature pattern that is bendable and very durable. Consequently, the proposed fabrication strategy for double curved panels is conditioned by the dimensions of the pattern's lines and their symmetry on x and y axes.



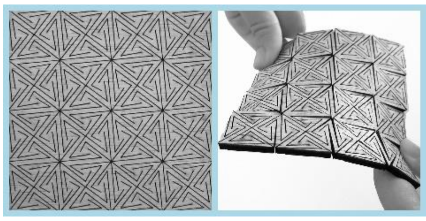
18. Drawing a meander that consists of curved segments, we observe that this pattern bends less than the original meander pattern, but it is more durable.



19. The shape of the original meander pattern is based on square shapes. To experiment with variations, a new meander pattern is designed based on hexagonal shapes. This is a double curvature pattern, which is bendable, but less durable than the original meander pattern. During the bending strength experiments, this timber plate broke to many pieces, as the stresses are distributed all over the surface due to the complexity of the pattern.



20. By converting the straight lines into curves, it emerges that the specimen is less bendable, but the durability is greatly increased.



21. This pattern is a variant of the meander pattern with triangular shapes. The maximum curvature of the timber plate is at the intersection points of the eight triangles. These points operate as hinges. The specimen can be heavily curved, but easily broken due to the many lines that meet at the intersection points.

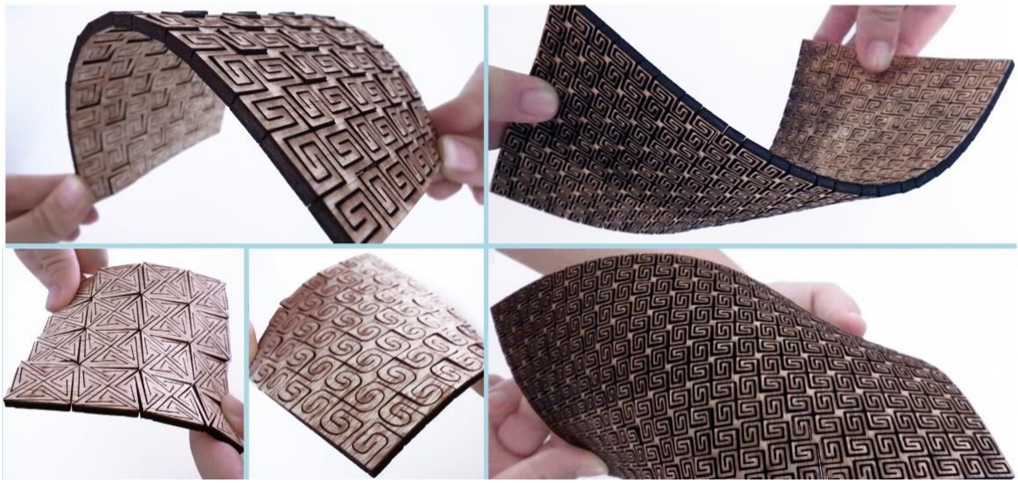


Figure. 9: Specimens of Meander Patterns

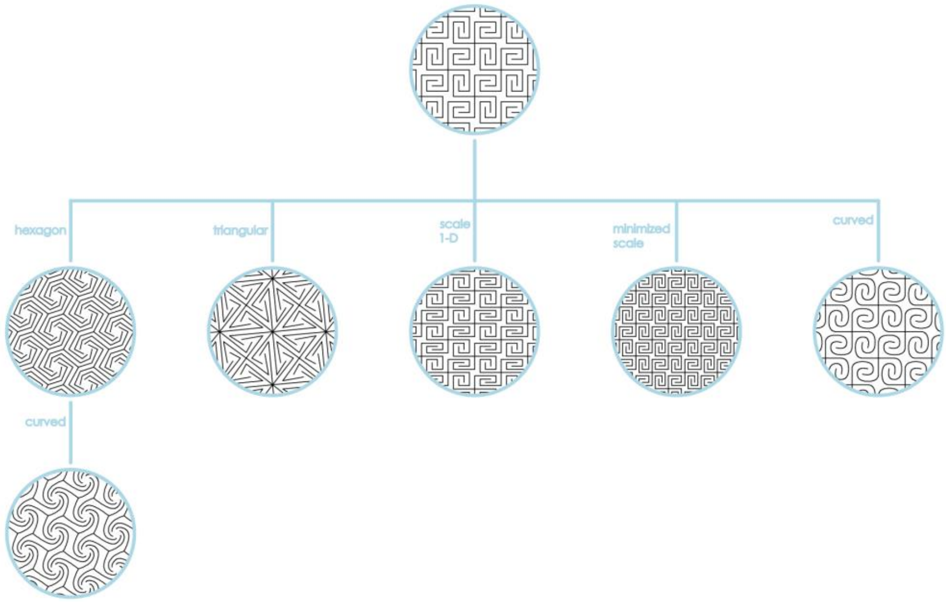
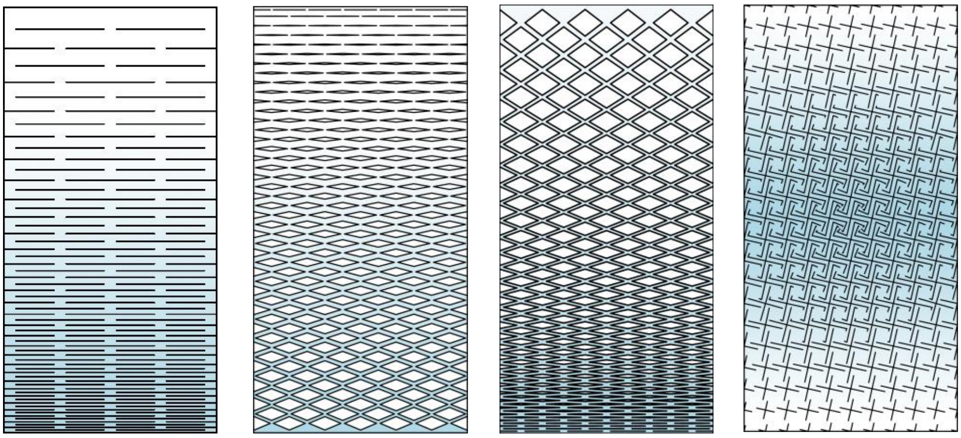


Figure. 10: Genealogy of Meander Patterns

Parametric patterns

The following experiment includes the changing of the surfaces' curvature, through variable spacing of the pattern elements. It is observed that the specimens are more flexible, as the lines of the patterns become denser, but when the distance between the patterns come close or smaller than 1mm, fracture of the specimen is possible. The specimen does not bend, when the distance between the pattern lines is high. In this experiment, the patterns are applied to a 20 x 10 cm wood surface in order to allow more space for the parametric variation of the spacing of lines. In the following diagrams, blue color gradient denotes the area of maximum curvature and in white the area of stiffness.



(a) (b) (c) (d)

a) This pattern is an evolution of Aaron Porterfield's linear pattern. The maximum spacing between lines is 1 cm and minimum is 0,11 cm. As the lines of the pattern become denser, the surface becomes more flexible and durable.

b) This pattern is combination of two patterns, the lines are transformed into diamonds. The first step was to set the number of the rows and the distance between them (2,9 mm), depending on the size of the larger diamond. As the shape of the diamonds grows, the lines of pattern get closer. Therefore, the specimen bends more at the point where the diamonds are larger.

c) This pattern is an evolution of the previous one, there is also a parametric transformation from lines to diamonds, but this specimen is denser. It was observed that this pattern is more bendable than the previous one, because the thickening of the lines is more noticeable.

d) Another parametric pattern was designed, based on the meander shape, by parametrically reducing the length of the pattern's lines, the meanders are transforming into crosses. This gives a rise to a pattern of double curvature, which is denser in the center of the specimen, for this reason the point of maximum curvature is located at the center of the surface. This pattern is slightly bendable, due to the short length and the lack of alignment of the lines.

As the lines of a pattern become denser, the degree of the curvature increases. The importance of the alignment of lines or shapes, their length and the distance between them must be taken into consideration while designing a pattern.

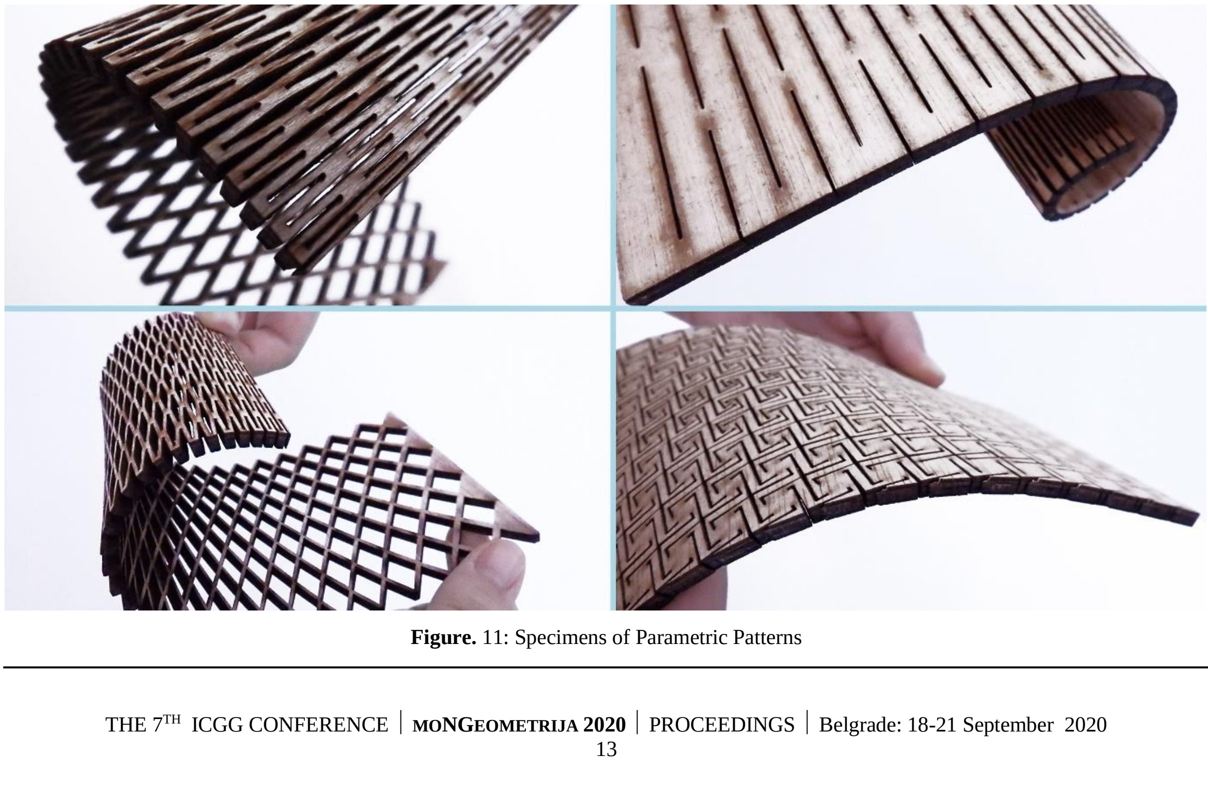


Figure. 11: Specimens of Parametric Patterns

CONCLUSIONS

Curvature

From this research it emerges that the kerf bending technique is highly dependent on the wood type. It is seen that when the kerfing is applied in natural wood, the bending is influenced by the orientation of the wood fibers. For this reason, for the single curvature patterns on natural wood, it is recommended that the pattern is applied parallel to the direction of the fibers. In case of application of the pattern perpendicular to the fibers, the fibers are seen to obstruct the bending of the timber plate. The curvature of a surface is also dependent on the thickness of the wood that is being used. The thicker the material, the sparser the applied pattern should be, in order to maintain the durability of the material.

Single curvature

Regarding the influence of a pattern on the surface curvature, it appeared that the patterns bend more when their lines are elongated and by increasing the density of the patterns. The lines of a pattern present discontinuity in order to keep the surface consistent. As the distance between the gaps of the lines is increasing, the curvature of the surface is reducing. It is necessary that some of the pattern elements are consistent until the boundaries of the surface. The more complex a pattern is, the less the surface bends.

Double curvature

It is essential that double curvature patterns are symmetrical in x and y axes, otherwise one of the two directions becomes dominant, and the pattern becomes a single curvature pattern. The double curvature patterns with offset shapes, present a high degree of bending, as the distance between the lines increases. On the other hand, the double curvature geometry motifs, such as meander, present high degree of curvature, as the distance between the lines reduces. As already mentioned previously, the durability of a surface is reduced when the curvature increases. However, this is not the case for the patterns with offset shapes, considering that their curvature increases by elongation of the length of their lines. It is possible to make a ruled surface by changing the orientation of linear patterns. Moreover, the curvature of the surface always follows the orientation of the lines of the patterns. The parametric patterns are applied to surfaces with variable curvature, their pattern dilutes where a low curvature degree is required, and where a higher degree of curvature is required the pattern becomes denser or the length of the lines extends.

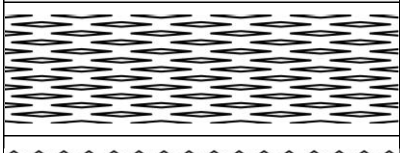
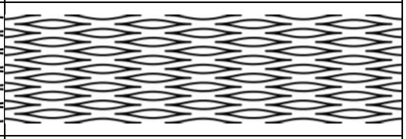
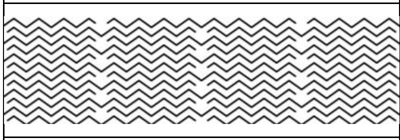
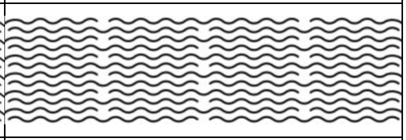
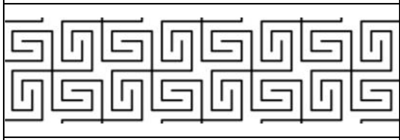
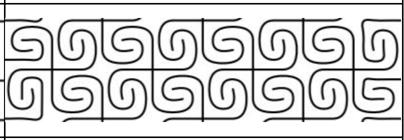
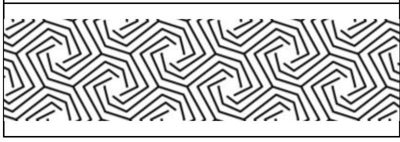
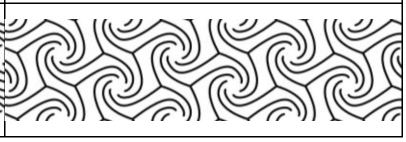
Bending strength

As the curvature increases, the strength and the deformation ability of the specimens decrease. In effect, the strength of the specimen decreases by the subtraction of material. During the tests for evaluating the bending strength limit of the specimens, the creation of a cracking route which followed the lines of the pattern was observed. The specimens broke suddenly in many pieces, after bending stress. While finding the bending strength limit of double curvature patterns, we observed the fragmentation of the pattern, due to its complexity, which is distributing the tension all over the surface.

Breakpoints

According to Aaron Porterfield, the angles of the linear patterns are points of fracture. For this reason, he designed a similar pattern by replacing the angles with curves, as shown in the first row of the table (Porterfield, 2005). Therefore, the question that emerges is whether the curvature of a specimen is affected by the convexity of the pattern's shapes. The first step in this process was to choose three patterns and to redesign them with curved segments, inspired by Aaron Porterfield's experiment. Comparing the curved patterns to the linear ones, certain differences between them were observed; the linear patterns are more bendable, but the curved patterns are more durable, because of the elimination of potential break points at the angles.

Table 4: Comparison of linear and curved patterns

Linear Patterns	*Curved Patterns*
	
	
	
	

The widespread use of parametric design tools and CNC machines make the manufacturing of bended surfaces with Kerf Bending method much easier than before. As a result, new techniques for wood bending, through the removal of material, are being developed and are constantly evolving. Both the development of new patterns and the knowledge of their advantages and limitations, as well as useful remarks on their curvature, durability and other characteristics will likely lead to new architecture examples using kerf bending as a method for timber constructions of complex geometries.

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