# Unfolding Timber

## A future of design

*Ana Gatóo[1], Antiopi Koronaki[2], Abhinav Chaudary[3], Yelda Gin[4], Darshil U. Shah[5], Eduardo Wiegand[6], Lars Hesselgren[7], Midori Ainoura[8], Ron Bakker[9], Michael H. Ramage[10]*
*[1,2,4,5,6,10]University of Cambridge [3,7,8,9]PLP Architecture*
*[1]{ag773|ak2260\yg362\dus20\ew508\mhr29}@cam.ac.uk*
*[2]{AChaudary|LHesselgren\MAinoura\RBakker}@plparchitecture*

*"Unfolding" is a pavilion comprised of six lightweight structures designed for the London Design Biennale 2021. "UnFolding" examines the potential for using engineered timber with digital tools to produce flexible interiors. The pavilion is folded through kerfing methods into fractal-based structures. Extensive research, testing and sample fabrication to acquire optimal flexibility of different timber members through kerf patterns was accomplished for the project.*

**Keywords:** *Engineered Timber, Unfolding Timber, Flexible Housing, Folding Structures, Timber Pavilion.*

## INTRODUCTION

"Unfolding" investigates some of the possibilities of engineered timber in the built environment. Designed for the London Design Biennale, "Unfolding" evokes a walk through the forest. The fractal folding pattern, a modification of the herringbone pattern, resembles trees branching up to the sky from their trunks. Engineered timber products are still quite new, hence we are far from imagining their full potential and identifying their most efficient uses (Fleming et al. 2014). Extensive fabrication and testing of different kerf patterns led to their optimal design to achieve the flexibility desired in each of the folds of the pavilion structures (Gatóo et al. 2021).

UnFolding studies the behaviour of kerfing for folding timber exploring how engineered timber can play a role in defining flexible spaces for affordable housing, how it can adapt to modern methods of construction and how it can respond to the needs of creating circular economies for the future, where buildings are designed to be disassembled.

## BACKGROUND

Addressing the urgent need of shifting towards modern methods of design and construction, sustainable materials and the design of spaces that are transformable, adaptable and demountable, engineered timber also has the potential to bring nature back to the places we live in. It is a natural material that we can grow, it stores carbon and can substitute materials that cause high $CO_2$ emissions (Churkina et al. 2020). Off-site production of engineered timber elements can also reduce waste, lower cost, increase construction speed and create a more pleasant urban experience (Ramage et al. 2017).

The 21st century has progressively been moving towards more flexibility in residential interiors. After living with the COVID-19 pandemic, flexibility of interior spaces has become crucial (Kennicott 2020). Overlapping different activities within a space can create difficult relations between users of the same space, including depression, anxiety and stress. And, in the current situation, a lack of flexibility in indoor spaces can also hinder work productivity (Capolongo et al. 2020). Due to the lack of space in social housing, flexible spaces are even more relevant. The current situation brings the opportunity to re-design the way we live. Flexible spaces in housing have social, economic, and environmental benefits and provide inhabitants with appropriate tools to accommodate changing needs throughout a lifetime (Schneider and Till, 2005). By creating flexible interiors, houses can adapt to users' needs. High flexibility in indoor spaces can ensure privacy for studying or working, as well as for relaxation or for children playing. By providing users with an empty space that can be filled in by them and with a modularity that can grow or be reduced with time, we can also provide them with a more affordable solution. With mass customization, the growth of digital fabrication factories for timber products, interior walls can become creative and affordable. Buying unpartitioned space and being able to expand it (or reduce it) in the future is an affordability strategy that has been studied and tested in the past (Rohe and Watson 2007).

A pavilion was designed to explore the behaviour and possibilities of folding timber for a future development of walls that can be folded.

Experimentation with different kerf patterns, scales and densities and digital cutting tools allowed us to achieve diverse forms and foldability combining parametric design and prototyping to generate optimized and efficient forms. This work brings together material and computational design to improve design with natural materials.

## THE PAVILION

"UnFolding" explores the ways in which timber can improve how we live through a light, flexible and transformable structure. The team used kerfing, a cutting method that can turn flat rigid panels into foldable or curved elements (Chen et al. 2020). The technique relies on designing the scoring or cutting patterns to fold or bend the surface to its target geometry. The topology and geometry of kerf patterns, fabrication processes with different equipment and types of wooden panels were explored, to develop a final installation of folded timber components.

The pavilion was designed for the London Design Biennale 2021, for one of the rooms on the mezzanine level of Somerset House, an 18th-century landmark building in London. The exhibition space reserved for the pavilion was approximately 80m$^2$ (11x7m) and 4m high. Vaulted ceilings gave the main characteristics to the exhibition space. Many variations in size, height, and location were investigated for the folded pieces during the design process. The final design of folded arching elements' directionality, width and height responded to the geometry and the location of the vaults and the separating walls, creating a dialogue with the form and the rhythm of the exhibition space (Figs. 1a and 1b). Accordingly, the pavilion consists of six folded timber structures, four of which are larger and aligned with the exhibition walls simulating a tunnel, while the remaining two smaller pieces are aligned with the bases of the vaults, facing inside. This arrangement allows the visitors to perceive the pavilion from different points of view. Due to the pandemic, a one-way navigation system with a minimum width of 0.9m was required within the exhibition space. Accordingly, the pavilion pieces were located in order to create two passages, hence visitors could experience the pavilion twice on their way in and way out respectively. These two passages change in width, getting narrower and wider. The passages' aim is to resemble a walk through the forest. The gap between these two passages varies between 0.9 to 1.4 m, giving a sneak peek of the smaller pieces in the middle. Folded pieces gradually get smaller from bottom to top, resembling trees branching up to the sky from their trunks. Exhibition lighting located in the middle of the ceiling infiltrates through the kerfing pattern, creating playful shadows on the walls.

Figures 1a) & 1b) UnFolding. London Design Biennale 2021.

## DESIGN

While kerfing has been widely used for the bending of timber into singly or doubly curved surfaces, this project explores its potential for folding flat timber panels through its application on a folding pattern. Two main streams of work were therefore identified: the study of the relationship between the parameters of the kerfing pattern and the generated material properties, as well as the development of a folding pattern.

### Folding pattern

This study explored the development of a folding pattern that changes in scale to simulate the branching structure of trees. Moreover, generating different densities of folds within a single sheet of material creates differentiated levels of stiffness for the final three-dimensional geometry and therefore enables a higher control over the properties of the final structure. This approach can also accelerate the fabrication process through the informed application of the folds.

The herringbone folding pattern was used as a basis for the development of the folding pattern. The initial set of small-scale paper models developed (see Fig. 2) led to the design of a modification of the herringbone pattern that changes in scale. The flat surfaces of the original pattern were subdivided through the introduction of a set of vertices along its width, as shown in Fig. 3. This process can be repeated recursively, allowing the fractal subdivision of the pattern within a single sheet of material. The position and number of the subdivision vertices can change to create diverse geometries. The folding pattern was then mathematically modelled using the mirror plane method (Mitani and Igarashi 2011). The developability of the fold pattern was hence validated, enabling the quick and robust evaluation of a variety of folding configurations.

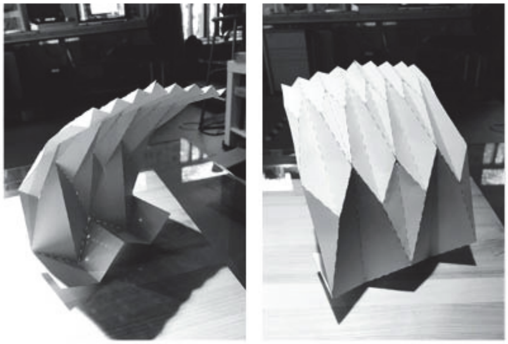


Figure 2 UnFolding. Paper model

### Kerfing pattern

Kerfing patterns deform the material by reducing its stiffness and increasing its flexibility. This deformation, depending on the type of pattern, can occur in one or two directions. Patterns that create deformations in one direction are called *linear* patterns (Fig. 4a) and in two, *meander* patterns (Fig. 4b) (Holterman 2018).

Different parameters can influence the degree of deformation and flexibility that a pattern can have: shape and direction of the pattern, density of the

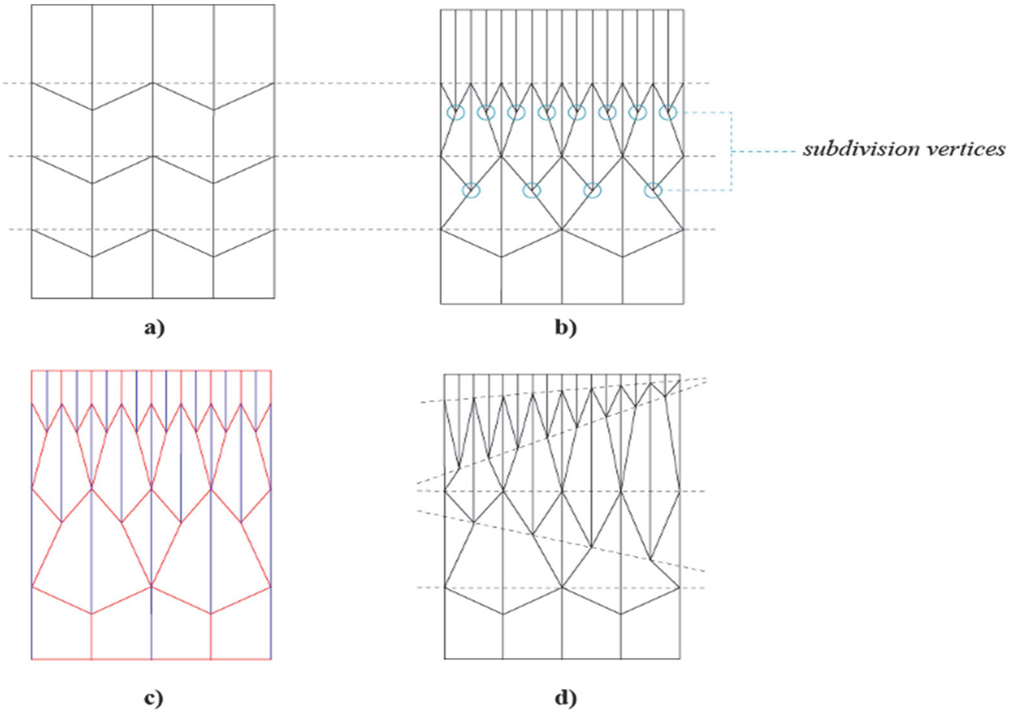


Figure 3
a) The original Herringbone pattern and b) the fractal pattern developed. c) The mountain (red) and valley (blue) folds of the pattern. d) Pattern variation

Figure 4
a) Linear pattern and b) Meander pattern

pattern, distance between pattern lines, scale and length of the pattern as well as the scale and length in relation to the material (Gatóo et al. 2021).

For the development of the singly curved fold lines within the pavilion, we focused on the exploration of linear patterns occurring in one direction. A set of experiments was carried out for the design of the kerfing in the vertices of the folding pattern. To select the appropriate pattern for the pavilion, flexibility properties of several patterns were explored and bending tests were conducted with the use of a testing rig (see Fig. 5). The findings are detailed in Gatóo et al. 2021.

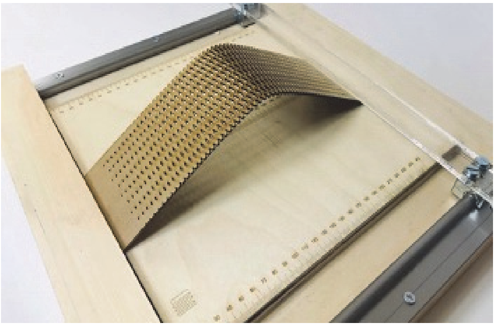


Figure 5
Testing rig

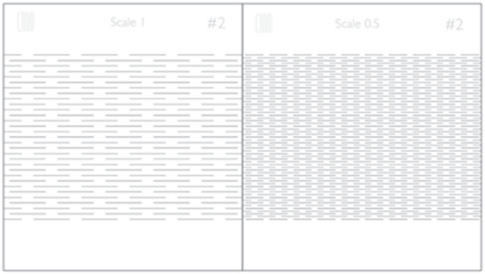


Figure 6
Straight lattice pattern

The pattern selected was the straight lattice pattern (see Fig. 6) due to its homogeneity. The straight lattice has a constant length line, avoiding any localized points of stress in the material.

Once the pattern was selected, several physical experiments were carried out to decide on the length of line, the distance between lines, the number of lines and the thickness of each of the lines in order to achieve the flexibility required.

The first samples were fabricated with a laser cutter into 2mm MDF. Several samples were created to test each of the parameters mentioned above (see fig. 7). When samples with different parameters had similar flexibility characteristics, the sample that provided a bigger resistance to breakage was selected.

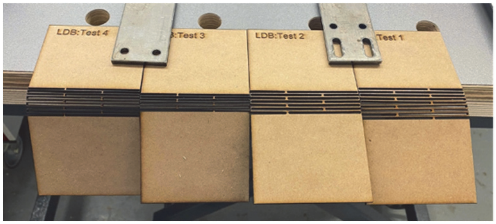


Figure 7
MDF 2mm test samples

The tests conducted demonstrated that, when the thickness of the material was scaled up, the pattern could be scaled up in a linear manner. The same principle was proved when scaling up from MDF 2mm to plywood 6mm and from plywood 6mm to 18mm.

Once the relationship between kerfing parameters and the generated curvature was established for the straight lines of the pattern, vertices with different folds were fabricated and tested. For the vertices, a series of trials were made in order to release the stress.

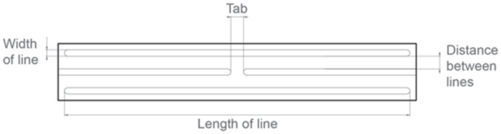


Figure 8
Unit cell of pattern

When the curvature of the MDF 2mm model was controlled through the geometry of the kerfing pattern, the process was scaled up to 6mm plywood. A handheld computer-aided milling tool was used in the beginning to fabricate single vertices and their correlative folds. These samples explored the design of the vertex to allow the flat timber sheet to fold without breaking.

The distance between two consecutive lines called a *tab* played a major role in the design of the kerfing pattern too (See Fig. 8). Folding lines inside the same sheet of plywood could not have less than two tabs to perform adequately and avoid breaking. When a folding line inside a plywood sheet had less than two tabs, the line had to be redesigned to resist high deformations and loads.

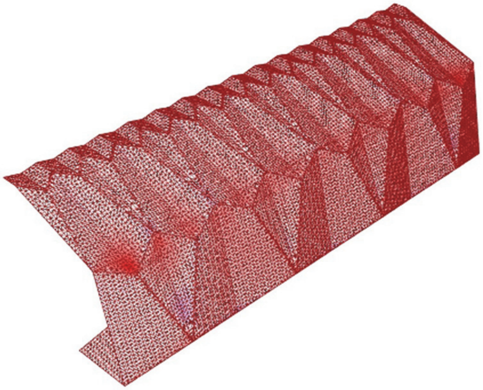


Figure 9
Initial structural analysis

## COMPUTATIONAL WORKFLOW

Once the kerfing pattern parameters were defined, the topology and geometry of the folding pattern were studied. An initial structural analysis was carried out within a parametric modelling environment to explore the relationship between the folding pattern and the structural performance. This analysis was carried out with Karamba3D within the grasshopper modelling environment and the structure was evaluated for self-weight (Karamba3D). For the scope of this experiment, continuous plywood sheets were assumed, without the consideration of the impact of the kerfing pattern on the structure. The folding pattern was optimized for an even distribution of stress through the surface articulation, as shown in Fig.9.

The next step was the application of the kerfing pattern. The unrolled geometry of the folded structure was initially generated and the kerfing pattern was then applied on the flat, two-dimensional geometry. The fold lines remained fixed during the study of the kerfing parameters, ensuring the developability of the generated design. A parametric model of the kerfing pattern was developed, enabling the rapid evaluation of different parameters, informed by the outcomes of the physical experiments. Once the values of the kerfing pattern parameters were defined, a structural analysis of the final design was carried out. The kerfing pattern was remapped on the three-dimensional, folded structure, which was then structurally analysed.

The computational workflow developed enabled a seamless flow of information and iterative calibration of the folded and unrolled geometry, as well as the physical experiments and computational modelling. Moreover, the developability of the folded structure enabled the direct application of the kerfing pattern on the two-dimensional geometry for the generation of the fabrication files. The application of the kerfing on the three-dimensional structure was therefore only required for the final structural analysis, accelerating the overall analysis and design process.

## FABRICATION AND ASSEMBLY

The fabrication and computational stages for the design of the pavilion went through an iterative process where one informed the other. The first step was to develop a paper model of a fractal origami structure. Once that was developed, the unfolded two-dimensional geometry was drawn in Rhino CAD.

### Kerfing pattern

A kerfing pattern was initially applied to the unfolded geometry in CAD scaled down for a 2mm MDF. At the beginning, the pavilion was envisioned to be made of 12mm plywood throughout and so the pattern was scaled down to 1/6 for an MDF of 2mm thickness. This initial kerf pattern was uniform throughout. The geometry at real scale had a width of line of 6mm, a length of line of 320mm, a distance between lines of 12mm and a width of 7 lines.

A first model was laser cut into two pieces of MDF 2mm. The pieces were fabricated to have an overlap so they could be glued and assembled to study its behaviour. See Figs. 10a) and 10b). This initial model provided insightful information regarding the kerfing pattern, structural performance and fabrication process. Through this model it was observed that the upper folds were not flexible enough. In addition, the two folds between the base and the wall were carrying all the weight of the wall structure and could easily collapse. Finally, a minimum number of tabs needed to be considered in each line of the geometry. When a line of pattern

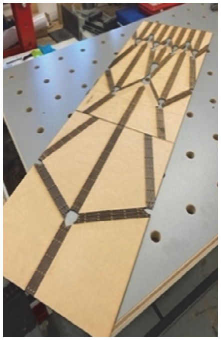
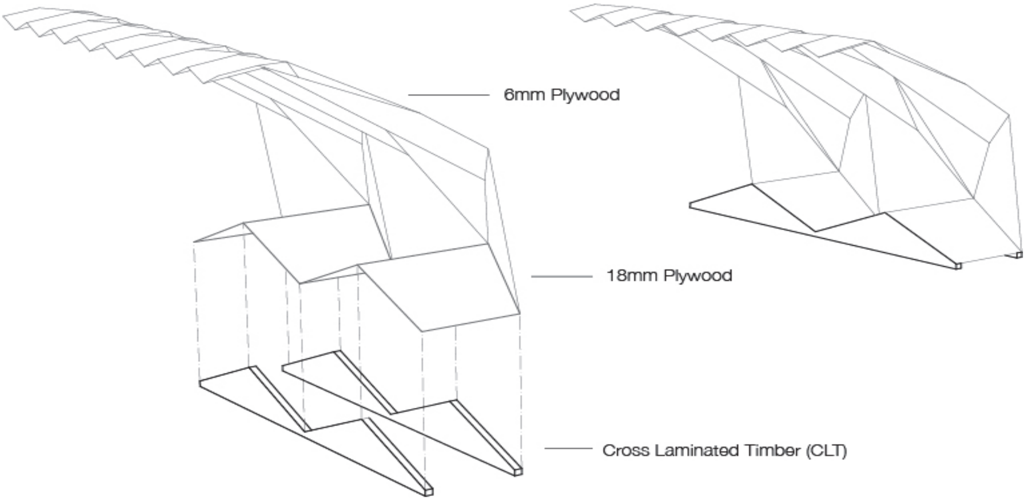


Figure 10a
MDF 2mm
unfolded geometry


Figure 10b
MDF 2mm model

Figure 11
3D Design with material selection



has several tabs, the forces and stress are divided between those. Moreover, providing at least two tabs per kerfing line provided substantial resistance to torsion/twisting. When the line is shorter as in the upper lines of folds, there are few tabs, and this can lead to breakage.

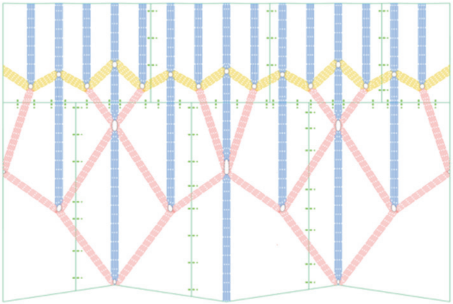
A series of steps were taken to address these challenges. Firstly, the minimum number of tabs was set to two. By introducing this parameter, the lines of the pattern needed to be shorter where the folding lines were also shorter.

The model was then scaled up to 12mm plywood to examine its performance. Due to the thickness of the material, the specific parameters of the kerfing pattern did not allow for the flexibility and folding behaviour required. It was then decided that the envelope would have 6mm plywood and a base made from 18mm plywood. In order to avoid overturning, the base, together with Cross Laminated Timber (CLT) supports would provide weight and stability (See Fig. 11). Regarding the pattern, the cut lines were reduced to a 3mm thickness and the distance between lines to 6mm.

The final pattern of the envelope of each folded line is shown in Fig. 12. The width of the cuts was 3mm throughout and fabricated with a 3mm up-down cut bit. The distance between lines was 9mm and constant throughout. The length of the lines varied depending on the structural performance of each individual folding pattern. The blue lines, requiring less stiffness, had a length of 127mm; the red lines had a length of 100mm; and the yellow lines had a length of 55mm. Both the red and the blue lines had a pattern width of 7 lines and the yellow ones of 9.

The reason to increase the width of the yellow pattern was to achieve a bigger flexibility without compromising its stiffness. Since the full-length

Figure 12
Final pattern



yellow folds were much shorter, in order to have the right number of tabs, it needed to have very short lines. By increasing the width, it increased the flexibility that had been lost by shortening the lines.

## Vertex design

Since the selected pattern folds in one direction, we decided to remove material from the vertex, where a doubly curved surface geometry was formed and stress was concentrated.

A study of different design options for the vertex was conducted. A first trial investigated not removing material at all (See Fig. 13a). This led to different lines colliding with each other. A second trial looked into removing just the bit of material that was making the lines collide (See Fig. 13b).

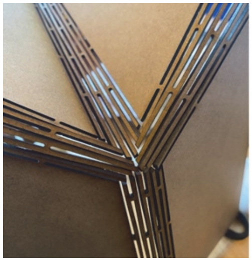


Figure 13a
Vertex with full length lines

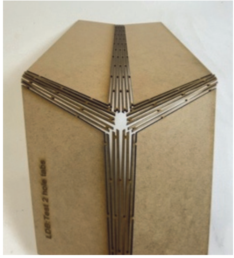


Figure 13b
Final vertex design

## Connectors

The next step was to design a connector to join the 6mm panels together. The aim was to use timber and avoid glue, in order to be able to disassemble and assemble the pavilion in the future elsewhere. The connector had to be easily fabricated with a CNC machine and provide stiffness to the joint. The connector was made of three parts, a front part, the "bow" which went through the panels, a back part that fixed the connector in place and a dowel that locked the connector. The front and back parts were made of 6mm plywood. Because they were precisely cut with a minimum clearance, and because of the friction of the connection, there was no need to lock the connector with the dowel and so the dowel was not used in the final design. See Fig. 14. After some trials, the connectors were placed on the unfolded geometry at a maximum distance of 240mm between them.

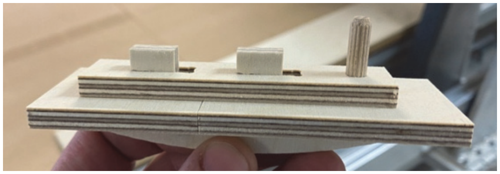
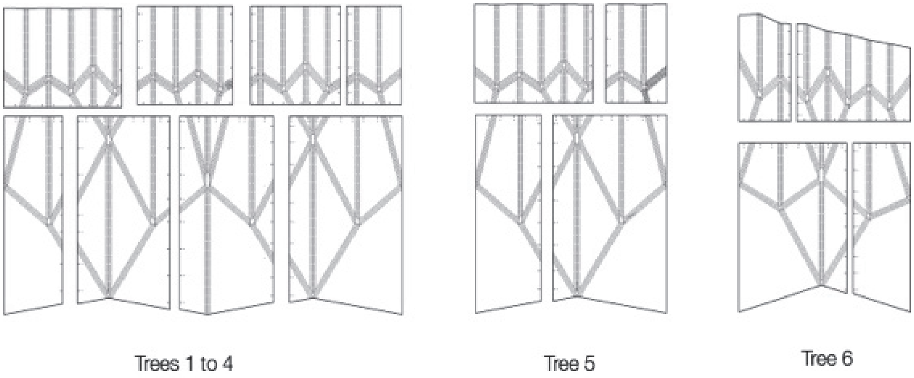


Figure 14
6mm ply connector for connecting different sheets.

## Structural design

As far as the structural performance is concerned, the structure was designed to be supported at its



Trees 1 to 4

Tree 5

Tree 6

Figure 15
Panel division of unfolded geometries

base, which was designed with increased structural weight to avoid overturning. This was achieved by differentiating the material properties and thickness throughout the pavilion.

More precisely, hardwood cross laminated timber was used for the supports, 18mm plywood for the base, joists and ribs and 6mm plywood for the envelope.

In addition to improving structural performance, fixing the kerfed plywood sheets to the base enables it to act as an actuator for the generation of the final geometry. More precisely, since the kerfing cuts are uniform throughout the material thickness, the sheet can fold in either direction. The base therefore defines the boundary conditions to create the final shape.

18mm plywood ribs and joists were added to the final structure to support the fabric canopy.

### Panel division

After designing the connectors and in order to use the sheets of plywood efficiently, the unrolled geometry was subdivided into the final components according to the maximum dimensions of plywood sheets available (1.22x2.44m). The cut lines were distributed in such a way to avoid edge continuity and allow for sufficient distance from the kerf lines. Enough space was left to place the holes for the front part of the connectors to go through the connection. The remaining unused material within each plywood sheet was used to fabricate the connectors, avoiding material waste, as demonstrated in Fig. 15.

### Fabrication, time and transport

The final design for the six tree geometries took ten days of fabrication with a CNC router. The CLT supports were cut by hand with an electrical circular saw.

The panels were then flat-packed and folded and assembled on site. Due to the sheet geometry of the folded panels through kerf patterns, the structures are light, easy to assemble and occupy minimum space when stored.

## CONCLUSIONS

Through the design and fabrication process of "UnFolding", the team was able to gain in-depth knowledge into the performance of timber when kerf patterns are applied. The pavilion proved that timber is an optimal material when looking into affordable, sustainable and easy to fabricate components that can be folded providing a high range of flexible partitions within our interior spaces. The technique brings the potential of using digital tools and the use of a sustainable and natural material for creating flexible panels that can be flat packed, folded on site, transformed and adapted as inhabitants need and ultimately disassembled for being reused, as demonstrated in Fig. 16.

This method of construction has a lot of potential and can be extrapolated to the next generation of buildings made from engineered timber were architects, engineers and designers, can work together with the forestry industry and manufacturers to create a circular economy in building materials.

By using engineered timber and exploring its potential, we can design sustainable cities with materials that we can grow bringing nature-based solutions back to the places we inhabit.

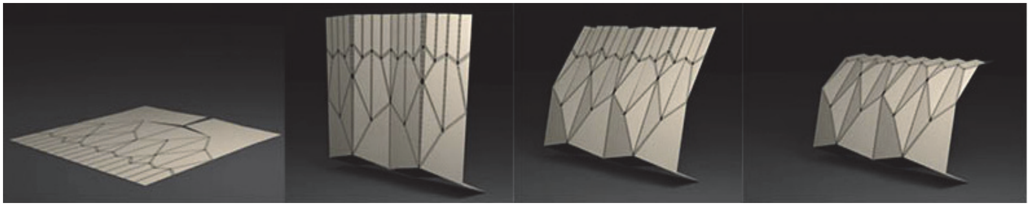


Fig. 16
Illustration of the pavilion from unfolded to folded.

## ACKNOWLEDGEMENT

This work is supported by the Centre for Digital Built Britain, the Construction Innovation Hub, PLP Architecture, Arts and Humanities Research Council, Laudes Foundation, Cambridge Trust, Grymsdyke Farm and American Hardwood Export Council.

## REFERENCES

Capolongo, S., Rebecchi, A., Buffoli, M., Appolloni, L., Signorelli, C., Fara, G.M. and D'Alessandro, D., 2020. "COVID-19 and cities: From urban health strategies to the pandemic challenge. A decalogue of public health opportunities." *Acta Bio Medica: Atenei Parmensis*, *91*(2), p.13.

Chen, R., Turman, C., Jiang, M., Kalantar, N., Moreno, M. and Muliana, A., 2020. "Mechanics of kerf patterns for creating freeform structures". *Acta Mechanica*, 231(9), pp.3499-3524**.**

Churkina, G., Organschi, A., Reyer, C.P., Ruff, A., Vinke, K., Liu, Z., Reck, B.K., Graedel, T.E. and Schellnhuber, H.J., 2020. "Buildings as a global carbon sink". *Nature Sustainability*, *3*(4), pp.269-276.

Fleming, P., Smith S., and Ramage, M.H., 2014. "Measuring-up in timber: a critical perspective on mid-and high-rise timber building design." *arq: Architectural Research Quarterly* 18, no. 1. 20-30.

Gatóo, A., Koronaki, A., Al Asali, M.W., Bukauskas, A., Gin, Y., Shah, D.U., Wiegand, E., Ramage, M.H., 2021. "Flexible and sustainable building components through kerf patterns.". *Proceedings of IASS Annual Symposium. International Association for Shell and Spatial Structures* (IASS).

Holterman, A., 2018. "Pattern Kerfing for Responsive Wooden Surfaces: A formal approach to produce flexible panels with acoustic performance."

Kennicott, P., 2020. "The pandemic has shown us what the future of architecture could be". *The Washington Post*. [cited 2022 January 15]. Available from: https://www.washingtonpost.com/magazine/2020/07/13/pandemic-has-shown-us-what-future-architecture-could-be/

Mitani, J., and Igarashi, T., 2011. "Interactive design of planar curved folding by reflection". *Pacific conference on computer graphics and applications*-short papers, Kaohsiung, Taiwan, pp. 21–23.

Ramage, M.H., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D.U., Wu, G., Yu, L., Fleming, P., Densley-Tingley, D. and Allwood, J., 2017. "The wood from the trees: The use of timber in construction." *Renewable and Sustainable Energy Reviews*, 68, pp.333-359

Rohe, W.M. and Watson, H.L. eds., 2007. "Chasing the American dream: New perspectives on affordable homeownership." *Cornell University Press*.

Schneider, T. and Till, J., 2005. "Flexible housing: opportunities and limits." *Arq: Architectural Research Quarterly*, 9(2), pp.157-166.

Welcome to Karamba3D (n.d). https://manual.karamba3d.com/.

Wilson, W., Barton, C. and Smith, L., 2018. "Tackling the under-supply of housing in England". *Briefing paper*, 7671.