COMPRESSION BASED GROWTH MODELLING

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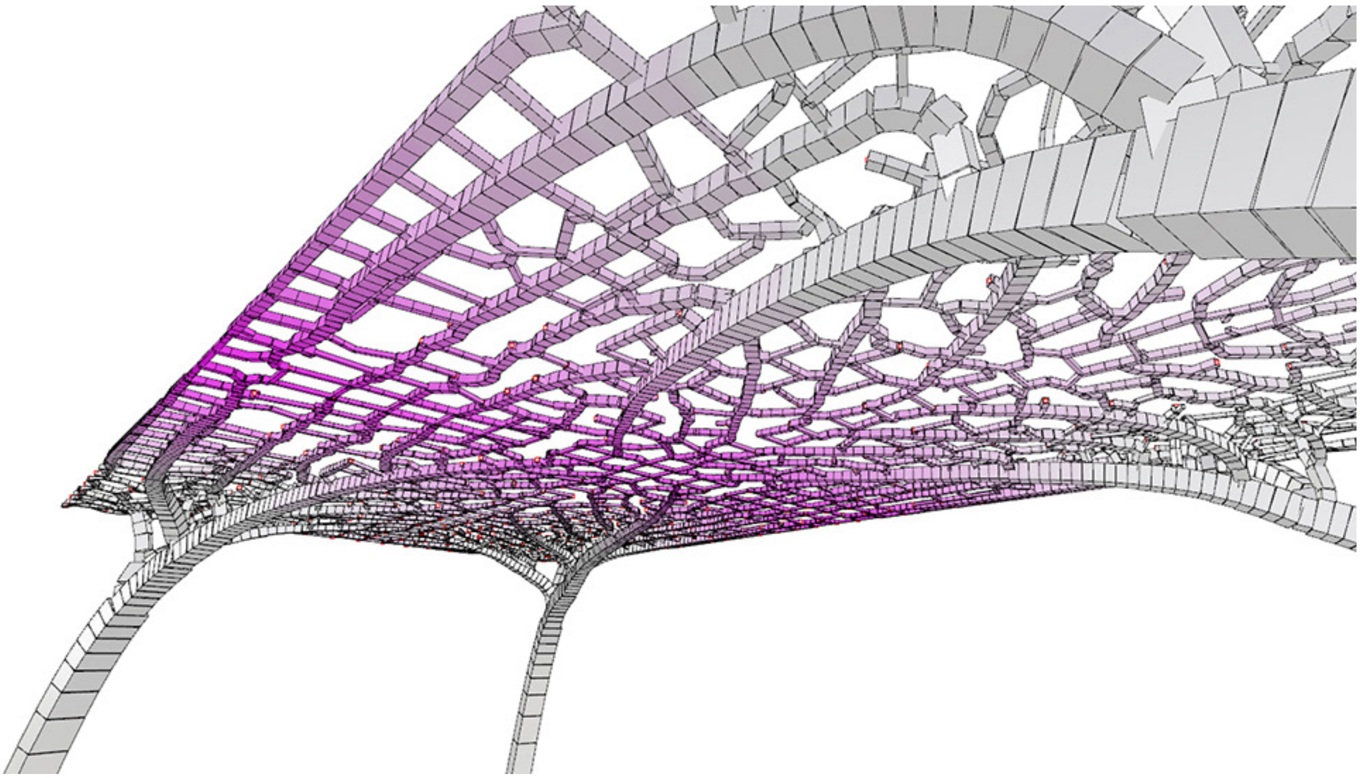
Orproject



1 Height-adjusted Reticulate Venation Structure (Klemmt 2014)

ABSTRACT

Venation structures in leaves fulfil both circulatory as well as structural functions within the organism they belong to. A possible digital simulation algorithm for the growth of venation, vascularisation or tree growth patterns has been described by the Department of Computer Science at the University of Calgary.

In modifying the algorithm for architectural applications, it is possible to generate a type of geometry in which a roof, the target surface of the simulation, is supported above a set of point supports, the seed points of the simulation. The resulting geometries can be similar in their appearance to the leaves of Victoria spp., in which the flat leaf is supported by the veins and a column like petiole from underneath.

Different ways of generating those geometries have been explored and digitally load-tested using Finite Element Analysis. Although the algorithm does not have an inherent logic of load transfer, the resulting structures perform well. In most cases, closed venation structures deflect less than open structures, which is in line with proposals that the formation of loops in leaves relates to structural performance.

NATURE AS INSPIRATION IN ARCHITECTURE

The analysis and abstraction of biological precedents for architectural and structural applications have found interests within the realm of a biomimetic design (El Ahmar 2011; Panchuk 2006). Organisms in the natural world have evolved over tens of thousands of years to be well adjusted to their environments. Nature is used as a model in design, but also as a measure to evaluate the performance of the design, and as a mentor from which we can extract as well as learn (Benyus 1997).

In architecture, biomimetic ideas are applied to a wide range of aspects, ranging from sustainability (Pawlyn 2011; Volstad and Boks 2012) to creating adaptive environments and material systems (Hensel 2006; Hensel and Menges 2007; Hensel et al. 2010; Weinstock 2010). The research of this paper focuses on the realm of structural engineering, in which the main aim is the optimization of structural efficiency (Waggoner and Kestner 2010; Gandomi et al. 2011). Other areas of biomimetics in structural engineering address material research (Barthelat 2007) or the integration of structures with other building systems (Yiatros et al. 2007).

The aim of the paper is a systemic comparison of leaf vein formations in order to evaluate if the structures may be suitable for load bearing applications. Tests using Finite Element Analysis are carried out under standardized conditions within a rectangular volume with even load and support distribution.

VENATION SYSTEMS

The vein networks found in leaves fulfill two functions: They form the circulatory system as well as the structural support of the leaf. Starting from the petiole, the network covers the surface area of the leaf and reaches the proximity of each cell (Roth-Nebelsick et al. 2001).

The vascular tissue contains the xylem and phloem which are enclosed by sheath cells. Angiospermae show the largest variety of ramifying patterns, which can form both dendritic (open, veins can diverge but not converge again) or reticulate topologies (closed, veins can diverge as well as converge again, causing anastomosis) (Sack and Scoffoni 2013).

The development of the leaf and its venation system happen during two distinct phases: An initial phase of cell proliferation and a second phase of cell expansion. The higher order veins develop during the initial phase. Their development is influenced by sources of the plant hormone auxin in the leaf (Sack and Scoffoni 2013).The lower order veins develop during the second stage of the leaf growth (Sack and Scoffoni 2013). Sachs formulated a canalization hypothesis for the development of the veins (Sachs 1991), however stress in the leaf surface may be a driving factor which can explain especially the abundance of closed loops in reticulate venation patterns (Laguna et al. 2008).

The structures developed for this paper have a different morphology from veins in leaves and are tested under vertical loading, whereas a leaf is mainly acting under bending. Also any structural performance of the lamina has been disregarded. However based on the above research, reticulate structures are expected to perform better during load testing than dendritic ones.

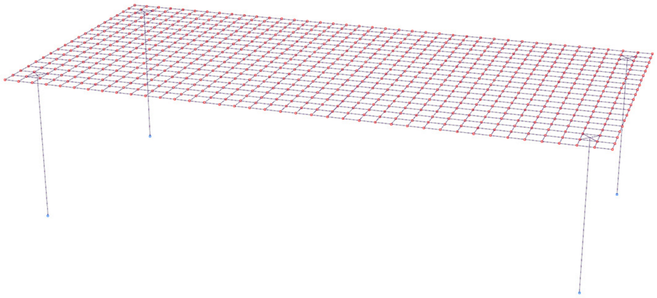
ALGORITHMIC SIMULATION OF VEIN DEVELOPMENT

Various models have been developed in order to describe and simulate the development of venation systems. Early attempts were based on L-Systems (Prusinkiewicz and Lindenmayer 1990). A canalization model based on auxin flux (Rolland-Lagan and Prusinkiewicz 2005) and an algorithm to generate both venation patterns and the dendritic structures of macrophyllis were proposed by the Biological Modelling and Visualization research group of the Department of Computer Science of the University of Calgary (Runions et al. 2005, 2007; Runions 2008). A model for the simulation of lower order anastomosing veins based on stress mitigation between the epidermis and mesophyll was proposed by Laguna et al. (Laguna et al. 2008).

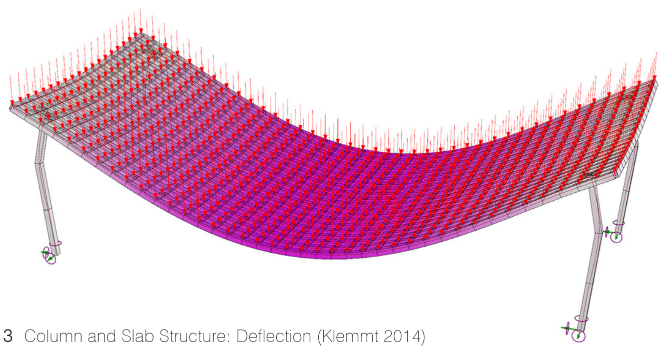
The models developed for this paper are based on the venation algorithm of the University of Calgary (Runions et al. 2005, 2007; Runions 2008). The algorithm uses as input the outline of the leaf and a set of seed nodes, which become part of the vein structure. It iteratively calculates three steps:

> The leaf envelope grows and is filled with auxin sources, which are abstracted points where photosynthesis occurs. Those act as the target points for the veins.
>
> Each target point identifies the vein node closest to it, which it will influence.
>
> Each vein node grows into the average direction of those target points which it is influenced by. A new vein node is positioned at a certain distance in this direction. If the vein reaches a target, this target becomes inactive.

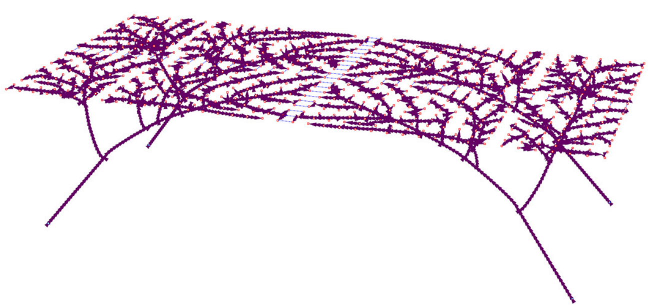
The width of the veins is calculated according to the amount of target points it supports.



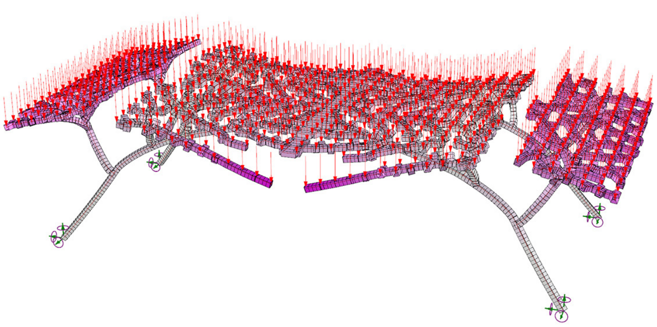
2 Column and Slab Structure: Centre Line Diagram (Klemmt 2014)



3 Column and Slab Structure: Deflection (Klemmt 2014)



4 Basic Dendritic Venation Structure: Centre Line Diagram (Klemmt 2014)



5 Basic Dendritic Venation Structure: Deflection (Klemmt 2014)

The algorithm can generate both dendritic and reticulate venation patterns. Dendritic venation patterns allow for a ramification of the veins, but those veins will not converge again. Reticulate venation patterns allow for anastomosis; veins can grow together again to form closed loops. The algorithm can generate those by allowing veins from different directions to grow towards the same target (Runions et al. 2005, 2007; Runions 2008).

The work by University of Calgary was aimed at generating patterns for computer games with the goal to generate a visual similarity to real leaves (Runions et al. 2005). The functions of the computational modelling are further seen as tools to understand the causality and development of plants (Prusinkiewicz & Runions 2012). This paper tries to take the existing research to a morphogenerative level with the aim to use the insight gained for the development of architectural structures.

ADJUSTMENT OF THE ALGORITHM

The algorithm has been reprogrammed to work in 3D using the Python programming language. The algorithm works by reaching each target. Like this, it can simulate the circulatory functions of leaf veins, but it does not include a logic for load transfer which would simulate the structural functions of the veins in leaves.

The algorithm has been adjusted in order to generate structures which can become support systems for architectural applications. For this paper, the architectural goal is to support a roof surface on top of point supports, the foundations. The venation structure is regarded as a network of structural members which could be steel columns and beams, or they could become a system of ribs underneath a compression-based surface.

The target points are regarded as loads on the roof. The roof surface is given and the set of target points on this surface is therefore static and is not altered during the simulation. The target points have been placed on a regularly spaced grid within a flat rectangle. This also removes the element of random from the simulation and allows a precise comparison of the results.

The seed points of the simulation are the point supports on the ground. The Cartesian Z dimension is used as the vertical direction.

GENERATION OF LEAF PATTERNS OF VICTORIA SPP: LEAVES OF VICTORIA SPP

Special interest was given to generate vein patterns which are similar to those of the leaves of Victoria spp., a water lily. The leaves have a flat surface which floats on top of the water, and are supported by the column like stem from underneath. This morphology reflects the common architectural requirement of having to support a flat roof or floor slab by columns. The leaf has a single stem to support it, whereas in buildings there are several columns to hold up the roof or floor slab.

Other than the xylem and phloem, he veins of plants located in anaerobe environments such as victoria spp. also contain aerenchyma, air-filled canals for the exchange of gases to the rhizomes (Schneider and Williamson 1993). The leaves of Victoria spp. are partly supported by the surrounding water, but still can support a significant weight on their own. Photos of babies sitting on the floating leaves are well known. However, the actual leaf surface is delicate and the load is taken by its venation structure (Ripley and Dana 1861).

FLOOR SPACE MAXIMIZATION

An aim of architectural spaces is to maximize the available floor space. Large or diagonal structural members may reduce this. The venation structure should therefore ideally grow up relatively straight in the beginning to form column like members, and start to branch out at a higher level.

The original algorithm grows directly towards the average location of the targets influencing the nodes. If the seed points are placed along the outside of the volume, this creates columns that can have a significant inclination and reduce the usable space underneath the roof.

One possible modification to the algorithm is to reset the calculated z coordinate of each node according to the current iteration. The z coordinate can be set to $z=H*(1-1/i)$. With z being the z-coordinate of the new vein node, H being the height of the roof which is to be supported, and i being the current iteration.

This results in a multiplicative inverse positioning of the heights of each node. The columns start as relatively straight and the members become flatter the later in the simulation they are created.

The overall distribution of the venation structure allows for a high usability of the space. However as not all target points are reached in the same iteration of the simulation, the endpoints of the venation network will be distorted from the flat distribution of the target points into a warped surface which is lower near the seed points. This geometry is similar to the leaves of other species of water plants such as Nelumbo.

Alternatively, the growth into the z direction can be accelerated the further a node is from the target surface. In each iteration the length of growth in the z direction Δz can be replaced by $\Delta z+a(H-z)$. With a being a constant number, H being the height of the roof which is to be supported, and z being the z-coordinate of the current vein node. Similarly to the first option, this results in columns which grow relatively straight in the beginning and which turn into a more horizontal growth towards the top. All target points are still reached within their flat plane.

As the aim of this paper is to compare the structural behavior of different systems, the exact positioning of the loads is of importance. The first system reaches the target points in a warped surface, a result which cannot be compared exactly to other flat distributions. Therefore the second method of height modification has been used for the models tested in this paper.

STRUCTURAL ANALYSIS SET-UP

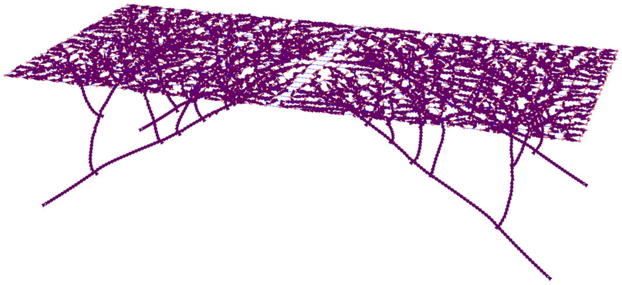
For the structural tests using Finite Element Analysis, the structures are analyzed within a rectangular box of 5m x 10m x 2.5m height. Evenly distributed loads are applied to the flat roof surface of the box with $2kN/m^2$. This surface is to be supported on four point supports which are placed near the four bottom corners of the box.

The aim of the test is a morphological comparison, therefore the morphologies to be tested are broken down into beam systems. Steel is used as the material for the analysis. All members are calculated as square solid sections. This allows for a simple calculation and scaling of the overall mass, although a larger structure will be built with different sections.

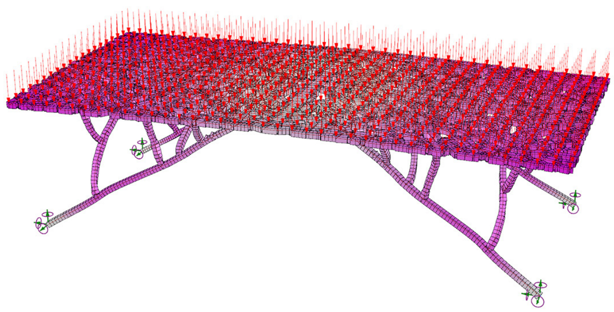
SYSTEMS FOR THE COMPARISON

The following types of structural systems are compared:

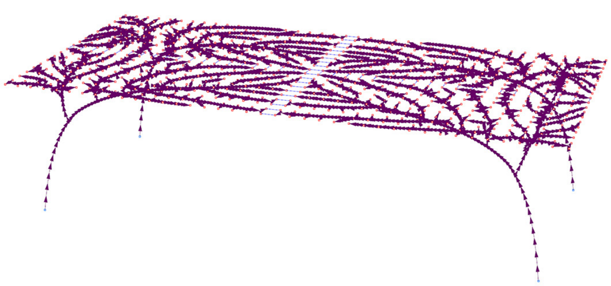
- A column and slab structure. A solid roof slab is supported on top of four vertical columns.
- Basic dendritic and reticulate venation systems. Those are generated using the algorithm described in point 1.
- Height adjusted dendritic and reticulate venation systems. Those have been generated using the growth adjustment as described in point 2.2.



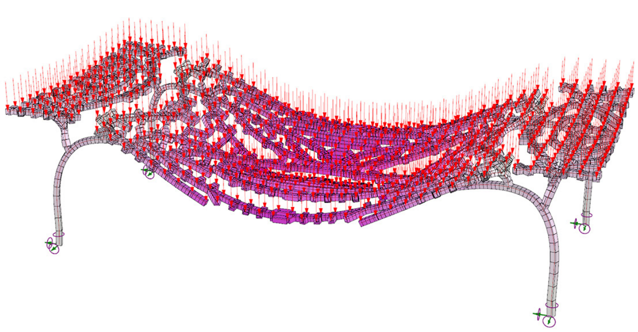
6 Basic Reticulate Venation Structure: Centre Line Diagram (Klemmt 2014)



7 Basic Reticulate Venation Structure: Deflection (Klemmt 2014)



8 Height Adjusted Dendritic Venation Structure: Centre Line Diagram (Klemmt 2014)



9 Height Adjusted Dendritic Venation Structure: Deflection (Klemmt 2014)

VALUES TO BE ANALYZED

The structural systems are analyzed for three behaviors:

Structural stability. The systems are analyzed for deflection under vertical loading.

Material usage. The amount of material required to build the structure. An adjusted deflection of the structure is calculated for a system, which has a fixed mass of 10,000 kg, all member sections are scaled evenly to achieve this.

Usable floor space. It is assumed that the space is to be used as a habitable room. The space is deemed usable if it is free of structural members up to a height of 2m. Any area within 0.5m of a structural centre line below 2m is regarded as unusable.

TEST RESULTS: COLUMN AND SLAB

Accumulative length of structural members: 397.828m

Accumulative mass of the structure: 31230kg

Maximum deflection under vertical loading: 17.186mm

Maximum deflection cross sections scaled to a mass of 10000kg: 166.969mm

Usable floor space: 46.858m²

BASIC DENDRITIC VENATION SYSTEM

Accumulative length of structural members: 260.678m

Accumulative mass of the structure: 20463kg

Maximum deflection under vertical loading: 7.653mm

Maximum deflection cross sections scaled to a mass of 10000kg: 31.769mm

Usable floor space: 36.139m²

BASIC RETICULATE VENATION SYSTEM

Accumulative length of structural members: 523.613m

Accumulative mass of the structure: 41104kg

Maximum deflection under vertical loading: 1.131mm

Maximum deflection cross sections scaled to a mass of 10000kg: 17.890mm

Usable floor space: 27.184m²

HEIGHT ADJUSTED DENDRITIC VENATION SYSTEM

(Accumulative length of structural members: 250.261m

Accumulative mass of the structure: 19646kg

Maximum deflection under vertical loading: 15.902mm

Maximum deflection cross sections scaled to a mass of 10000kg: 61.156mm

Usable floor space: 43.450m²

HEIGHT ADJUSTED RETICULATE VENATION SYSTEM

Accumulative length of structural members: 439.807m

Accumulative mass of the structure: 34525kg

Maximum deflection under vertical loading: 5.692mm

Maximum deflection cross sections scaled to a mass of 10000kg: 65.853mm

Usable floor space: 43.124m²

EVALUATION: USABLE FLOOR SPACE

The full floor space of the tested room is 50m². The column and slab structure has the largest usable floor space with more than 46.858m² available. The basic venation structures both have members which cut through the space diagonally and significantly reduce the available floor space, leaving 36.139m² and 27.184m² respectively. The resulting room can be regarded as difficult to use.

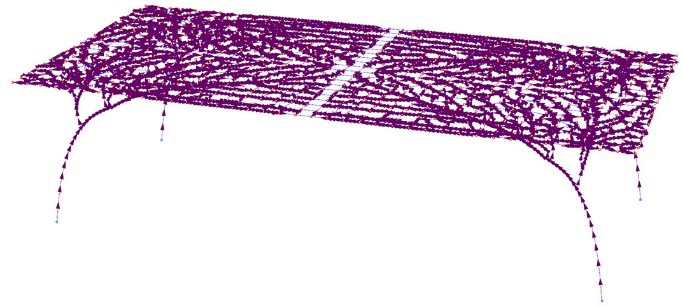
The height adjusted venation structures, which have been developed using the height based growth influence as described in section 2.2, both have a usable floor space which is slightly less but close to that of the column and slab structure. The resulting rooms have 43.450m² and 43.124m² of usable space and can be regarded as functional.

DEFLECTION

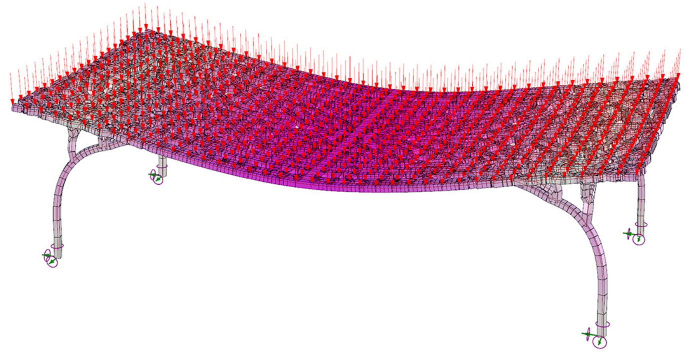
In order to be able to compare the deflection of the structures, their mass has been equalized by scaling the cross section of the members. The cross sections are still identical within each structure, but differ between the systems. The mass of each structure after scaling is 10,000kg.

The column and slab structure has the highest deflection, 166.969mm. The two versions of the basic venation systems have the lowest with 31.769mm and 17.890mm. Although they only occupy slightly more space of the room, the height adjusted venation systems have a significantly lower deflection than the column and slab structure, 61.156mm and 65.853mm.

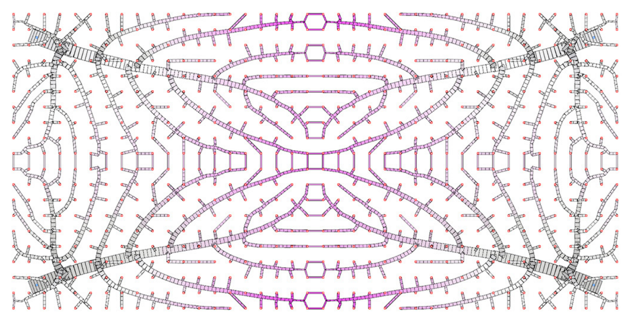
Between the two versions of the basic venation structures, the reticulate system performs better than the dendritic system, deflecting by only 17.89mm compared to the 31.769mm of the dendritic system. The deformed structure shows clearly how the separate areas of the system are breaking apart due to missing cross members, which the reticulate system has. This is in line with the proposal that the closed loops in venation patterns relate to structural performance.



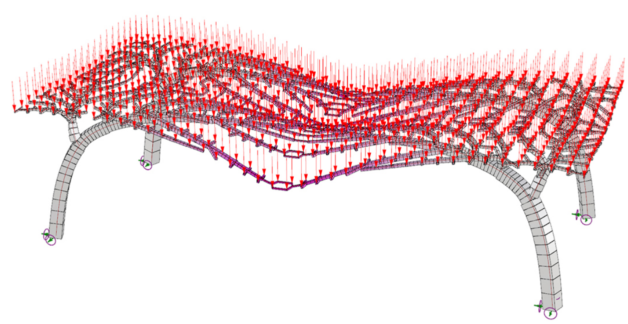
10 Height Adjusted Reticulate Venation Structure: Centre Line Diagram (Klemmt 2014)



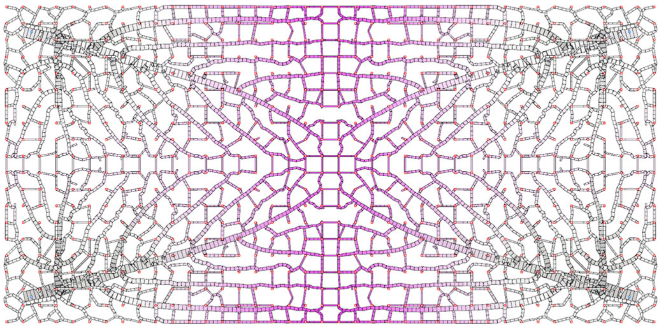
11 Height Adjusted Reticulate Venation Structure: Deflection (Klemmt 2014)



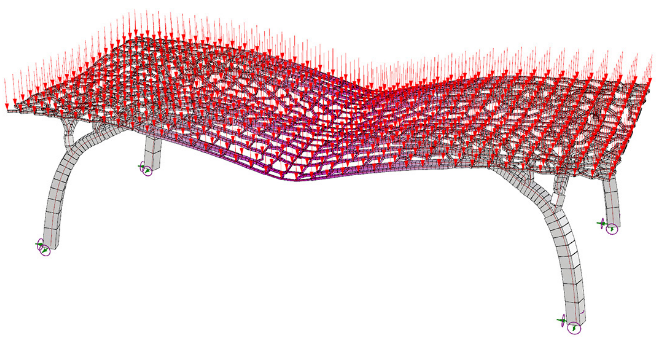
12 Height Adjusted Dendritic Venation System with Valued Cross Sections: Plan (Klemmt 2014)



13 Height Adjusted Dendritic Venation System with Valued Cross Sections: Deflection (Klemmt 2014)



14 Height Adjusted Reticulate Venation System with Valued Cross Sections: Plan (Klemmt 2014)



15 Height Adjusted Reticulate Venation System with Valued Cross Sections: Deflection (Klemmt 2014)

The comparison of the two height adjusted venation systems behaves differently: One may have expected that as in the basic venation systems, the dendritic system should have a higher deflection due to the separation of different areas. However, the two systems perform very similar and the reticulate structure has a slightly higher deflection, 65.853mm compared to 61.156mm.

This can be explained by the fact that the reticulate system has a high amount of structural members in the upper area, which have the same cross section as the columns at the bottom of the system. Those column members are transferring a much higher load than the upper members and therefore increase the overall deflection. To test this, the cross section sizes have been adjusted in two further models.

VALUED CROSS SECTIONS CHANNEL DIAMETER

The veins of leaves have varying diameters, partly relating to the amount of cells they service and the amount of fluid which is passing through them (Sack and Scoffoni 2013). In the same way, the size of the veins in the simulation can be adjusted according to the amount of target points it reaches, and in the structural systems the cross section of each member can be adjusted according to the amount of load points it supports. As the cross section sizes may have caused the unexpected comparison between the two height adjusted venation structures, those two systems have been rebuilt and tested with valued cross sections according to the amount of supported load points.

HEIGHT ADJUSTED DENDRITIC VENATION SYSTEM WITH VALUED CROSS SECTIONS

Maximum deflection cross sections scaled to a mass of 10,000kg: 16.962mm

HEIGHT ADJUSTED RETICULATE VENATION SYSTEM WITH VALUED CROSS SECTIONS

Maximum deflection cross sections scaled to a mass of 10,000kg: 11.986mm

COMPARISON

The adjustment to valued cross sections which reflect the amount of load points a member carries significantly improves the performance of the systems, reducing the deflection from 61.156mm and 65.853mm to 16.962mm and 11.986mm respectively. With valued cross sections, the reticulate venation system performs better than the dendritic system. The deflected model shows how the dendritic system separates into different areas similar to the deflection of the dendritic systems with constant cross sections.

CONCLUSIONS AND FUTURE WORK

The digital simulation of the venation structures is based on a circulatory algorithm, which is based on physically reaching its targets; it does not have any logic of structural load transfer. Nevertheless the geometries that have been generated by the algorithm perform very well as load bearing structures, significantly better than a column and slab system. The height adjusted systems reduce the available space underneath the structure only slightly more than a column and slab system. The structures therefore seem suitable for architectural applications, either as a frame system or as a set of ribs underneath a shell structure. The architectural other than structural possibilities of the systems need to be explored with further work.

It appears that due to a lack of larger beams between the columns, except for the basic venation systems the structures seem to have a weak point along the central axes. The simulation can be adjusted and the implementation of a structural logic into the algorithm is likely to yield improved results. A structural growth algorithm could also react to specific material definitions and generate multi-storey systems.

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IMAGE CREDITS

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CHRISTOPH KLEMMT graduated from the Architectural Association in London in 2004. He has worked amongst others for Tezuka Architects, Lab Architecture Studio and Zaha Hadid Architects. In 2008 he co-founded Orproject, an architect's office specializing in advanced geometries with an ecologic agenda. Christoph Klemmt lectured widely and taught at the AA Visiting Schools, Tsinghua University, Tongji University, University of Wuppertal. Orproject exhibited at the Palais De Tokyo in Paris, the China National Museum in Beijing, the Milan International Furniture Fair. Orproject won multiple awards and was featured in Domus, Frame, Wired, Surface, The Guardian, Metro SCMP, Thomson Reuters, BBC online.