Strategies for Metallic Vault Structures

Aluminium composite panels used as structural elements

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This article explains parametric, fabrication and teaching strategies used during a workshop for constructing a full scale, self supporting, vault metal structure realized with parametric manufacturing methods. The key aim is to construct a small size, easy assembled and transportable pavilion, while focusing on new design and construction methods of a façade system in which the structure, joint and skin will integrate functions in a unifying structural system. For the investigation, we explore materials commonly used in façade industry, such as aluminum profiles and aluminium composite panels (ACP).

Keywords: Spring System Simulation, Catenary, Digital Fabrication and Construction, ACPs, Aluminium profiles

INTRODUCTION

In order to achieve a new kind of paradigm for architectural practice, through the teaching inside workshops, we are trying to establish a close relation with the manufacturing industry and take advantage of the new technological advances in the material sector to demonstrate how parametric strategies and digital manufacturing techniques provide effective connection between design and production in real scale. This workshop research focus on discrete surface relaxation geometry (meshes), as a construction system, to explore the material usage of aluminum profiles and ACPs where the typical roles of cladding and support structure are reversed. The cladding panels are used as structural elements and the aluminium profiles are used as a mesh that weaves the two elements together. The advantage of using computational tools is to examine the design potentials of emerging and dynamic phenomena through series of algorithmic strategies for the form-finding optimization, structural analysis and cutting patterns of a structure called Calycas (see figure 1).
OBJECTIVES - RESEARCH AREA
The main objective of the workshop was to construct a real scale pavilion combining two metal materials and to understand the skin facade behavior and structure.

Vault Finding
Based on the concept that the triangular mesh is the most efficient from structural point of view and having the advantage of planarity of faces (Pottmann et al. 2007), this investigation starts from testing spring systems and catenary behaviour on flat triangular meshes with symmetry in the outline shape and a center point.

Particle-spring systems are based on lumped masses, called particles, which are connected by linear elastic springs. Each spring is assigned a constant axial stiffness, an initial length, and a damping coefficient. Springs generate a force when displaced from their rest length. (Kilian and Ochsendorf 2005). The benefits of Particle-Spring Systems and physics engine simulator (Kangaroo) for form-finding, is that help us to investigate the behaviour of a catenary in real time. Similary, previously architects and engineers Antoni Gaudi with its hanging cables, Frei Otto tensile structures and Eladio Dieste with the Gaussian Vault techniques, have used as main principle the Robert Hooke law.

Looking at nature as inspiration, the purpose was to flip the metal catenary structure, optimize the amount of triangles by applying different physical forces goals such as gravity, min max edge lengths, self-weight loads and six anchor points and some boundary conditions like openings and total height.

Node Challenges
Emerging from the interdisciplinary field of architectural geometry, the design research of Calycas is engaged with discrete freeform structures, multilayer surfaces and geometrical problems occurring, while looking for a construction solution. A very common method, in order to realize the intended shape of the vault as steel-glass construction, in principle is easy to find a 3d triangular mesh, which approximates that shape, and let beams follow the edges of this mesh, with glass panels covering the faces. (Wallner and Pottmann 2011). To follow a similar design logic, it is necessary to solve problems related with the generation of the beams and their planarity.

Pottmann has proved that only in triangle meshes near-spherical, the mesh offset can be at approximately constant distance and node axis can be approximately orthogonal to the mesh, which means an optimized node is a mesh vertex where the central planes of all emanating beams pass through a fixed line, the axis of the node (Pottmann 2007). Otherwise, the beams to meet in the same node axes have to twist, which results in non-planarity of the beams. In the case of catenary mesh vaults it is also difficult to avoid elongated triangles in some parts of the structure.

Structural Speculations
The collaboration with the facade engineering company proved to be quite effective. Considering material aspects, performance and distribution of forces and loads along the structure’s joints, the investigation ranges from the vault form-finding to the assembly and how the two case materials are affecting each other and cooperate under external forces. Materials are chosen for each structural component based on experience, properties and aesthetics.

The intention was to integrate functions by using one connector and cover the mesh faces with hexagonal folded panels in an attempt to test if the ACP is able to support the lateral forces of the structure. With the Millipede library of very fast structural analysis algorithms for linear elastic systems, the beams are analyzed as frame elements (see figure 2a) and the mesh as shell element (see figure 2b). The structure is considered to be fixed to the ground. The advantage of using this software is that it can work inside Grasshopper, so the form-finding is connected with the FEM analysis. The deflection results of the frame analysis for the global structure are helping to identify the weak areas and possible location of reinforcement of beams, in the bottom of the leg, where...
an extra folded piece is added. The shell FE analysis is locating the maximum deflection area, where the joints proved to need reinforcement in case of extra loads. The ACP hexagons reduce the deflection of the aluminum frames due to their rigidity (see figure 2c). Computational methods allow high-level integration and simulation of the geometry. Physical materialization though, is the best way to test the performance of the system.

Experience from previous projects was also valuable. A similar to Calycas, but wood, structure was constructed in same scale, with double disc connection system and no covered faces (see figure 3). Another project, related with this research, is the LaDose. An hexagonal free-form mesh structure was the starting point for the fabrication of discrete surfaces. For the generation of the beams, many different processes were tested, in order to achieve the most efficient construction method, made of laser cut aluminum folded stripes, connected with threaded rods (see figure 4).

WORKSHOP METHODOLOGY
The workshop teaching agenda is arranged in three phases from the design to fabrication: Modeling, manufacturing and assembling techniques. The goal is to explain step by step the parametric process, systemizing the geometrical relationships, together for the modeling and manufacturing techniques. Using as an organizing and teaching method a very efficient tool of Grasshopper, the cluster, is permitting a clear understanding of each part and manageable manipulation of the geometrical result in one workflow.

The advantage of breaking a big definition in many clusters is to find and edit more easily the information needed, for example, which are the specific inputs necessary to orient or unroll pieces, while the outputs of the clusters continue to be linked with the rest of the definition to update data. The simultaneous feedback between each phase, due to all clusters connection, facilitates the optimization of the design workflow. This method is also beneficial when many
people are contributing in the same project, but in different parts of the definition.

**PARAMETRIC MODELING STRATEGIES**

The metallic vault is generated from 3 component systems for the beams, joints and skin:

- A self-supporting triangular mesh, generates the beams, made of aluminum bars, 3mm
- 63 mesh nodes, generate the connectors between the beams, made of ACP, 4mm
- An hexagonal mesh generates extrusions, made of same ACP.

The vertices of the triangular mesh are locating the position of the discs (R50mm), placed perpendicular to the normal of each point. The same vertices are moved towards the center point of the base boundary triangle, generating the edges of the beams. Each edge of triangle is scaled based on a specific distance from the node. The new nodes generate hexagons, which are scaled and moved to generate 3D openings, as extrusions towards the direction of the face normal.

In this stage the design is informed by the machinic fabrication techniques of ACP. In the fabrication manual, the principles of milling for folding, the thickness of the crease line is depending on the folding angle. For sharp edges (down to 45°) a V-groove of 135° should be made. The base of the groove should always be flat and about 2 to 3mm wide (see figure 5). The panels are routed in the rear side, extracting the aluminium sheet and part of the core (see figure 6). The scaled new edges for the generation of the hexagons is taking in account this parameter, in order to leave necessary material close to the corners for the folding.

![Routing details from ACP fabrication manual.](image)

![Frame and Shell Visualizations of distribution of deflection.](image)
Based on the above design logic, 4 linked clusters are formulating the parametric strategy: 'Beam Construct', 'Disc Construct', 'Hexagon Construct' and 'Intersections'. The outputs of each system are defined and placed as inputs for the rest. For example, some of the outputs of 'Beam Construct' cluster and 'Disc Construct' cluster are inputs for 'Intersections' cluster. This actually is the most challenging part to understand, where the information is taken from and which intersection line belongs to which beam and disc.

Using the same definition, students could generate variations for each component system and discuss about different methods of joining and assembling which is essential when it comes to such complex geometries and assemble time is the main constraint. The intention to incorporate the ACP skin as part of the structural system is achieved by designing the hexagonal components to join directly to the beams with the ear technique and 3 metal screws for each beam. The beams and the discs are designed to be connected with the dovetail technique facilitate the assembly.

**MATERIALIZATION PHASE**

**Manufacturing Techniques**

The benefit of visiting some of the largest manufacturing industries of aluminum is to get introduced to the manufacturing and coating process of aluminum and composites and their unique properties. almost unlimited possibilities of design profiles and universal applications of the material.

In this phase of the workshop, we are explaining all the steps necessary to convert the 3d to 2d elements, in order to introduce participants to the production process and digital manufacturing techniques with 3-axis CNC router and laser cutter. Again, the parametric strategy is formed in clusters, one for each system: 'Orientation of beams and slits', 'orientation of discs and slits', 'unroll hexagons and number faces'. Considering that all pieces are different, numbering process is essential for each element and slit, so all numbers are engraved. All processes, from modelling to fabrication are automated inside the same Grasshopper definition, counting material cost and cutting time.

**Construction Logic**

Along with the design of the pavilion, the construction logic is conceived in such a way that the structure can be assembled and disassembled easily and transported as 4 parts, three legs and top head. Counting the help of 24 students, the 159 aluminum bars and 63 discs were organized by number and the 45 ACP pieces were folded and secured with screws and bolts (see figure 7). Various aspects related with safety, order, scale, forces, tools and time were resolved in an empirical way before construction.
Assemble Logic
For the assembly, 4 groups of 6 students and one supervisor, were responsible for each part of the structure (see figure 8). A code system diagram developed for this project demonstrates the number and location of pieces, the construction logic behind and the interconnection of the modeling and manufacturing process (see figure 9). Black numbers represent discs and those numbers are the same as the vertices numbers coming from the mesh. The green numbers correspond to the beams. The blue numbers belong to the hexagons, which are the same as the face numbers of the initial mesh. The triangle between discs
54, 10 and 29 shows where the connection between 4 parts is located. The table on the right side of diagram shows the connectivity of the vertices (discs) that correspond to the beams and the hexagons to the faces. Finally, all four parts were lifted together in order to be connected with the discs between (see figure10).

CONCLUSIONS
The aluminium composite panel that was used weighed twice as much as the originally planned panels, because it had a fire rated core instead of a core made of HDPE. This extra weight caused a failure in the connecting discs made from ACP. The ACP material was not able to support the lateral and buckling forces of the structure with the increased self weight. Therefore the discs were replaced with discs made from steel.

The workflow went almost as expected, although some aspects in the design of Calycas need to be optimized, like the joint design system and especially, the connection system between the 4 parts. Further studies include a different type of geometry and material, or a 3d printed optimized connector, instead of the planar discs. Although, the coordination of the student teams worked very well, the assemble process could be taken further with an efficient way for securing the 4 parts, in order to reduce the amount of people necessary to build a bigger structure.

Further contribution to the market, will be interesting to include design and digital fabrication of different types of mass production aluminum profiles so each piece will not need to be CNC machined.
The ACP material, as a skin component, has possibilities and needs additional research, as in cases of 3d façade systems, for environmental analysis and structural performance incorporation, as mentioned in an open discussion during the exhibition and international conference, estimating future trends on building envelopes.

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SPECIFICATIONS
Materials: Silver Metallic FR (fire resistant) aluminium composite panels 3200 x 1250 x 4 mm, aluminum sheets 3 mm or 30 bars of 5000 x 60 x 3 mm, screws and bolts. Machines/Tools: Laser Cutter, CNC Router/Hammer. Dimensions: Weight <150 kg, 3.2 x 3.7 x 2.6 m.

REFERENCES
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