An innovative fabrication process from rolled helicoidal steel strips

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Abstract

"Metal Euplectella Folie" is a prototype which explores an innovative design and manufacturing method for free-form architecture. Four 40m long by 0.4m wide by 1.5mm thick steel sheets, each cut to a unique pattern and then spiral-wrapped, form a sculptural tube assembled without the need for any adjustment, plans or jigs.

This experimental construction is inspired both by the structural concept of the deep-sea sponge "Euplectella Aspergillum" - a thin-walled shell stiffened by helicoidal fins - and by the industrial process for fabricating helicoidal pipes - manufactured by wrapping a continuous strip of constant width. By adopting a strip of variable width, a new range of potential forms may be explored.

This shaping process takes advantage of the property of developable surfaces that allows complex three-dimensional objects to be formed from flat cut shapes by simple bending.

Keywords: Developable surfaces, elastic bending, spiral tube, architectural geometry, innovative process

1 Introduction

Doubly-curved freeform surfaces are rarely built as they are first designed. A discipline in its own right has emerged over the last fifteen years dealing with strategies of rationalization to translate architectural intent into building feasibility. From the Computer Graphics perspective it is known as "Architectural Geometry"[1], as from the engineering and technology point of view it is called "Construction-Aware Design"[2].

The typical approach is to decompose the freeform skins into manufacturable panels.

Clearly, flat panels are a first response, whether triangular or quadrangular. A whole generation of engineers have made extensive use of special surfaces (translation, rotation or homothetical surfaces) that automatically generate flat quadrangles [3]. Recently, Mesnil et al. contributed to extending the field of these surfaces [4].

However, the use of flat panels contradicts the expression of the curvature which is often a major design intent. The cylindrical panels used in the Eiffel Tower's first floor pavilions faithfully reflect the design surface [5]. Although more expensive, these panels remain in an industrial manufacturing process since today's numerically controlled bending machines enable the fabrication of cylindrical toughened glass panels of different radii without using a mould.

These two primitives have the property to be isometric to the Euclidean plane, i.e. can be unfolded without stretching or tearing. The family of surfaces possessing this property are the developable surfaces: a pure bending process can transform standard flat elements (sold in sheets or coils) into complex three-dimensional objects. The Ductal panels of the Fondation Louis Vuitton are a relevant example of this [6].

This deformation kinematics make developable surfaces good candidates for elastic shaping as we will see later on. This approach could be related to form-finding of elastic structures [7].

The experimental structure « Metal Euplectella Folie », first exhibited at the Design Modeling Symposium 2017, has been constructed as part of the PhD thesis "Building with developable surfaces" completed at the Navier Laboratory in Ecole de Ponts et Chaussées in close collaboration with the engineering office T/E/S/S and steel contractor Viry.

The architectural intents at the origin of the project were a free-form tube that could be walked through and whose mechanical capacities had to be sufficient to span about ten metres.

2 Cross-inspirations

2.1 Cylindrical helicoidal tube

The manufacturing technique of the prototype is based on the industrial process for fabricating helicoidal pipes. Typically, large section thin-walled tubes are manufactured from a continuous straight strip of constant width wound into a coil. Helically formed, the first long edge of the strip is bonded to the second long edge after one turn.

The major industrial applications are:

- Spiral paper tubes made of multilayer glued kraft paper for paper or fabric roll as well as concrete column formwork;
- Ventilation duct made of thin sheet metal assembled by crimping;
- Large foundation pipes made of thick sheet metal with full penetration welding (Figure 1).

The advantage of this system lies in the continuous fabrication process and the ability to reach a high productivity of tubes with a considerable length.

During the process, it should be noted that the assembly tool for gluing, crimping or welding is in a fixed position whereas the tube describes a helicoidal movement: linear coupling of translation and rotation allows a constant running speed of the helix [8].

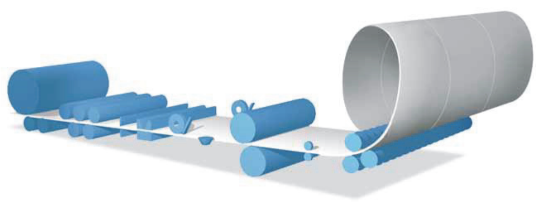

Figure 1. Spirally welded steel pipes production line (Arcelor Mittal)

2.2 Euplectella Aspergillum

Euplectella Aspergillum is a deep-sea, sediment dwelling sponge found in the Western Pacific. Its siliceous skeleton is formed from biological glass spicules, intricately arranged in a seven-level structural hierarchy (Figure 2), which generates a remarkable degree of flexural rigidity [9].

The morphology of the sponge inspired both the cylindrical topology for the organic shape of the project and its structural concept – a thin-walled shell stiffened by helicoidal fins.

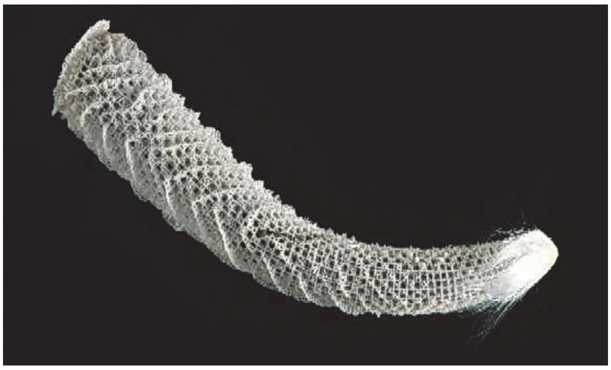

Figure 2. Euplectella Aspergillum

3 Morphogenesis

3.1 Geometrical concept

Unlike the case of cylindrical helicoidal pipes, by adopting a strip of variable width, a new range of potential shapes may be explored (Figure 3).

Conversely, starting from a given doubly curved form, a helicoidal curve may be drawn on this surface and be the guiding curve for the generation of a developable surface. Once unrolled, this strip is the cutting pattern of the three- dimensional form.

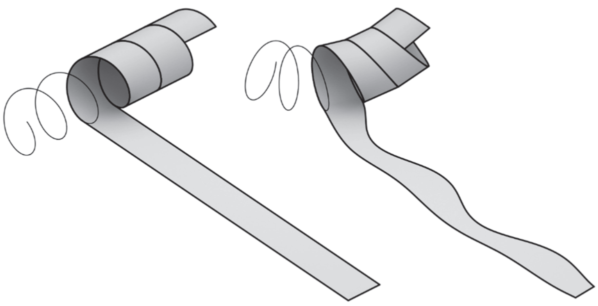

Figure 3. Cylindrical and freeform helicoidal tubes

3.2 Constraints

At an early stage of the process, three major constrains initiated the design of the pavilion. A parametric 3D model was implemented in order to integrate these variables but also to anticipate the many unknown ones.

It was subsequently enhanced to generate the shop drawings of the sheet metal cutting patterns. This continuous digital chain enabled multiple iterations and refinement of the geometry.

3.2.1 Ergonomics

The design intent of passing through the tube required minimum dimensions:

- Min height: 1,80m
- Min width: 0,5m measured at 1,5m high

3.2.2 Mechanics

For a better control of the form and a limited use of heavy equipment, the deformation of the materials should remain in the elastic range.

The Euler–Bernoulli beam theory can give a first approximation of the bending stresses in the final shape. It is given as a function of E (Young modulus), t (thickness) and R (radius of curvature) by:

$$\sigma = (\mathrm{E.t})/(2.\mathrm{R}) \qquad (1)$$

In our case, a 1,5mm steel sheet of grade S235 has a minimum radius before plastification: $R_{min} = 0{,}67m$.

3.2.3 Shipping

The time schedule and the difficulty of intervention on a long period on site led us to fully assemble the prototype in the steel fabricator's workshop.

Consequently, the bounding box of the prototype should be limited by the standard capacity of a truck trailer: 13.70m long, 2.48m wide, 2.76m high.

3.3 Steps of geometrical modelling

3.3.1 Reference surface

Architectural and technical constraints (outlined above and translated into geometrical terms) were integrated into the parametric 3D model of the reference surface which is defined by six successive cross-sections (Figure 6- a).

3.3.2 Double network of helices

The reference surface is inscribed with a double network of helices, which serve as generators for the components of the construction: four dextral helices in red and twenty-four sinistral helices in green (Figure 6 - b).

For architectural reasons, the form is generated by four strips rather than only one as shown in Figure 3 : the pitch of the helix is larger and provides a more easily readable spiral aspect.

3.3.3 Four developable strips

The four dextral helices are used as edge curves for a semi-discretization of the reference surface. Four interlaced developable strips, each of about 40m long and 40cm wide, were developed by direct parametrization, i.e. by finding ruling lines with a constant tangent plane along them (Figure 6 - c).

Indeed, for two spatial curves $\mathcal{C}_A$ and $\mathcal{C}_B$, if A is a fixed point on $\mathcal{C}_A$ (tangent vector $\overrightarrow{T_A}$) and B a moving point on $\mathcal{C}_B$ (tangent vector $\overrightarrow{T_B}$), finding a ruling line in A (Figure 4) is equivalent to finding the location of B such that the determinant

$$Det\left(\overrightarrow{T_A}, \overrightarrow{T_B}, \overrightarrow{AB}\right) = 0 \qquad (2)$$

In the case of helices, the determinant vanishes for several positions of point B (one solution at each turn). Proximity detection gives a valuable clue to find the appropriate solution (Figure 5).

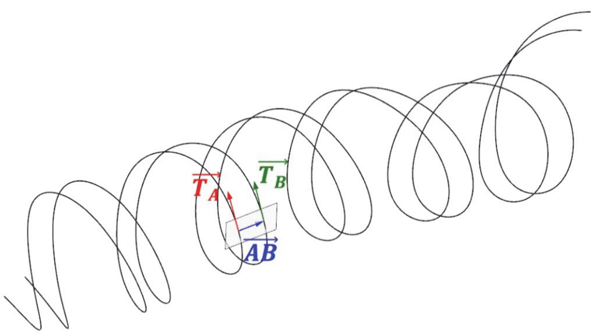

Figure 4. Definition of the tangent plane

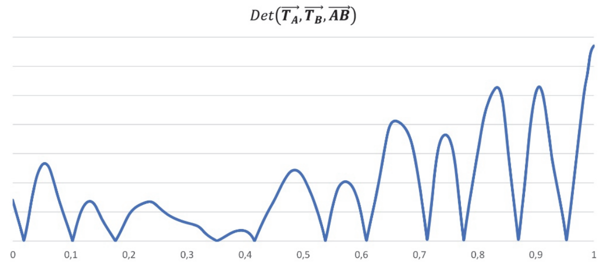

Figure 5. Value of the determinant with fixed point A and moving point B covering the whole curve $\mathcal{C}_B$

3.3.4 Four developable normal surfaces

The four dextral helices also generate four normal surfaces (Figure 6 - d).

The normal surfaces are not strictly developable since the helices are not located along the principal curvature lines.

Tang et al. [10] describe the geometry of developable strips as envelopes of planes of the Darboux frame. If $(\vec{t}, \vec{b}, \vec{n})$ defines a positively oriented orthonormal basis attached to each point P of the curve where κ_g, κ_n and τ_g are the geodesic curvature, normal curvature and geodesic torsion, the direction $\vec{r}$ of a ruling at point P is given by:

$$\vec{r} = \kappa_g \vec{n} + \tau_g \vec{t} \qquad (3)$$

This formula highlights that the rulings are normal to the reference surface when $\tau_g = 0$, i.e. along the principal curvature lines.

Schling et al.[11] find themselves in a similar situation when they generated developable surfaces along asymptotic lines. They applied an additional twisting moment to align the generatrices along the normal of the surface.

It is assumed that the same operation could be applied due to the narrowness of the fins and their weak torsional resistance.

3.3.5 Building components

The twenty-four sinistral helices are used to divide the strips and fins into easily handled, off the shelf components (Figure 6 - e).

It should also be noted that a fixing point between panels and fins is located at the intersection of each helix network.

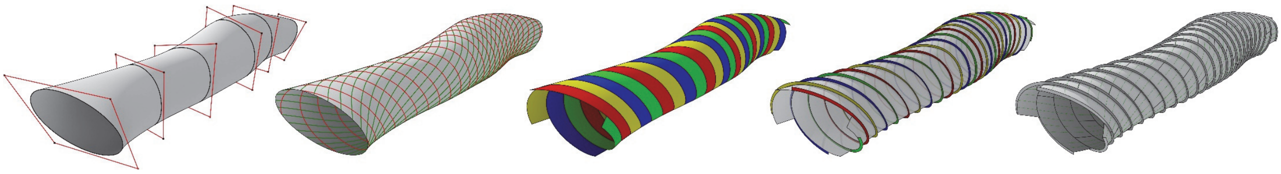

Figure 6. Steps of geometrical modelling: a - Reference surface, b - Double network of helices, c - Four developable strips, d - Four developable normal surfaces, e - Building components

4 Fabrication

4.1 Building materials

4.1.1 Panels

The panels are made of galvanised carbon steel, grade S235. Their average dimensions (1,5m long by 0,4m wide) and thickness guided the choice towards laser cutting.

4.1.2 Fins

The fins are made of crude carbon steel grade S235, 4mm thick. Their relatively similar shapes allowed an efficient nesting in standard 1,5m by 3m sheet metal for plasma cutting.

4.1.3 Fixing points

Only one type of bolt but with two lengths of shank were used: hexagonal bolt M8 (shank length 15/20mm) and cap nut.

4.2 Assembly

Due to nesting optimisation, the components came in a random sequence (Figure 9-a). Thus, the first step was to sort panels and fins according to a given naming convention (number of the strip and number of the panel/fin within the strip).

The second step - maybe the toughest one - was to close the first ring and thus lock elastic potential energy. The first four panels and fins are shown in Figure 9-b.

Once in a horizontal position, the last step is to install the panels and fins one-by-one to the assembled part that remains motionless (Figure 9-c, d). It may be noted that this process is the inverse of the industrial fabrication process of cylindrical spiral tubes where the assembly tool is in a fixed position whereas the tube describes a helicoidal movement.

The assembly is carried out without the need for any jigs or formwork. The information of the form is embedded in the cutting pattern of the panels and fins. Simply ensuring the correspondence of matching curved edges generates the three-dimensional form with high fidelity to the design 3D model.

The prototype was realized with no assembly plan nor any other information than the nomenclature engraved on the surface of panels and fins (Figure 7).

The time needed to assemble was approximatively four days with two people.

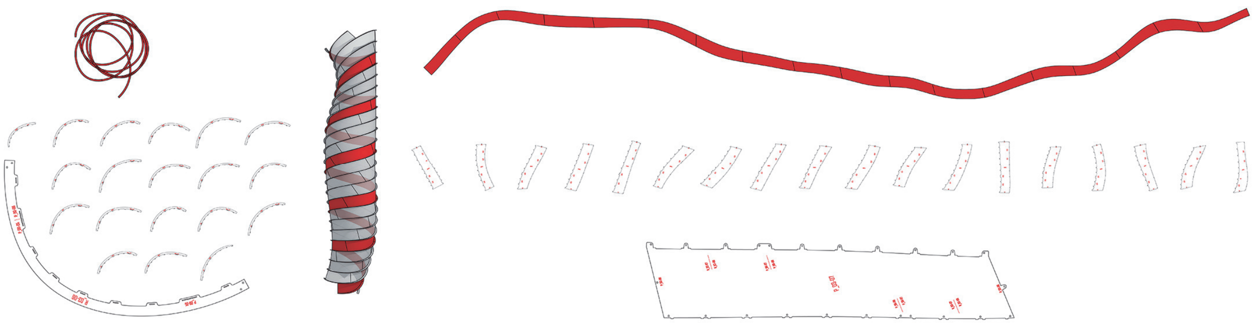

Figure 7. Cutting patterns showing one of the four strips of 18 panels and one of the four strips of 19 fins

4.3 Assembly detail

4.3.1 Kinematics

The principle is closed to a keyed mortise and tenon joint (Figure 8).

Panel 1 (in red) with a tenon is inserted inside the mortise of the fin (in green). Panel 2 (in blue) overlaps the tenon. At the end, the assembly is locked by the key (hexagonal bolt, cap nut and washers).

The edges of the panels only have point-contacts thanks to the shoulders located on both sides of the fins. These open joints enable the light to pass through and reveal the spiral geometry (Figure 11-b).

To prevent lateral torsional buckling, the fin is usually rigidly linked to the plate to provide stiffness. It is not locally the case here as the fin can rotate along the tangent of the helix. However, the curvature of the fin axis provides a torsional stability.

However, in case of local overload, a lateral displacement of the top fiber of the fin is observed, indicating the start of lateral buckling.

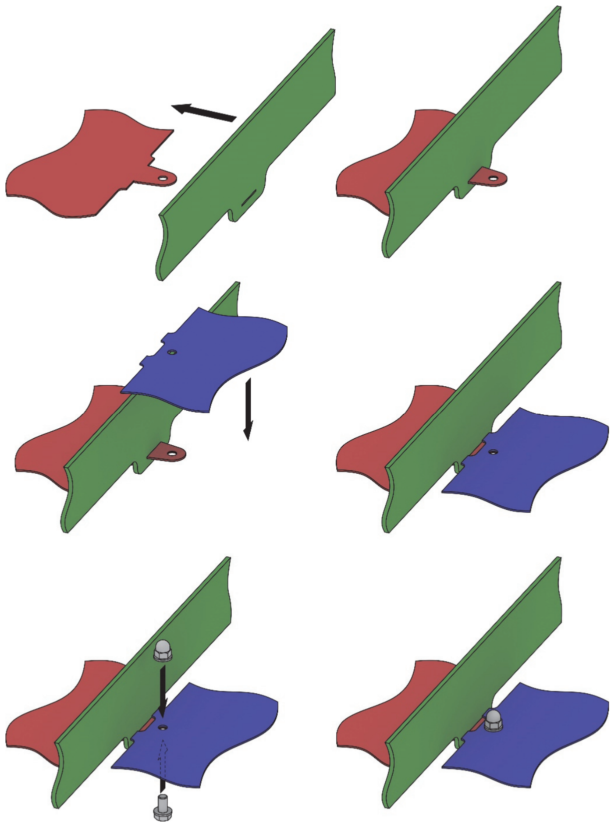

Figure 8. Kinematics of the assembly detail

Figure 9. Assembly steps of the prototype

5 Conclusions and discussions

In this article we have described an innovative building system making complex geometries possible by utilising the geometrical and mechanical properties of the developable surfaces.

The assembly is carried out without the need for any adjustment, plans or jigs. This avoids the use of heavy equipment and a fast-track building process.

Several in-depth studies or further investigations could be considered.

The prototype exhibits high structural performances: it spans approximately 10m while being lightweight (22kg/m² of shell). Parametric studies could enhance the structural behaviour by optimizing the global form of the shell as well as the material distribution.

The built prototype seems to match the 3D model with a high precision. However, metrology studies could bring to light divergences, especially due to elastic potential energy stored during the shaping process or the clearance of the mechanical fastening. Two studies are planned in the near future: a global one by image-based 3D reconstruction and a local one by measurement of the width of the open joints.

The complexity of the prototype form has been deliberately limited for time and shipping reasons. Free of these constraints, it would be useful to understand the range of geometrical variability the system could cover before it reaches its technological or mechanical limits.

Finally, an ongoing study is exploring other topologies based on the same principle of developable helices: multi-fork tubes inspired by Francis [12] drawings.

Figure 10. Trinoid: physical model

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Figure 11. Metal Euplectella Folie a - at Ecole des Ponts et Chaussées, b - inside view

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