Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

BAYA algorithm: characterization of the behaviour of braided structural shells

Quentin CHEF*[b], Marc LEYRAL[ab], Marc HYMANS[b]

* *Construire l'Architecture* research team
17 rue Championnet, 75018 Paris
quentin.chef@gmail.com

[a] AMP Research Unit, ENSA Paris-La Villette, Paris
[b] *Construire l'Architecture* research team

Abstract

The use of naturel fibers dates back at least to the Neolithic period. People around the world have employed braiding techniques and basketry craft to design a large panel of objects, clothes, furniture, boats, etc. In the field of construction, we can witness the use of braided natural fibers in numerous vernacular shelters, but they are generally limited to non-structural filling elements. The lack of description of the braided structures behavior in the literature is underlying that these kinds of techniques were not commonly used for a structural purpose.

The aim of our research is to demonstrate the feasibility of designing and building structural wicker braided shells for architectural purposes, and to provide designers with the necessary tools for this process. Thanks to the theoretical and experimental study of a braided specimen at a local scale, we defined the relation between density and orientation of the stems and the fields of principal stresses on an idealized continuous loaded surface: "each field of stress is related to an optimal braiding". These data are filling an algorithm, BAYA, making design and optimization of braided shells accessible and easy to use for architects and practitioners. This innovative research is demonstrated by the realization of full-scale benches with a load capacity of about 100kg during a scientific challenge event organized by the École des Ponts ParisTech in 2023 and 2024.

Keywords: wicker, shells, braiding, weaving, dynamic relaxation, grasshopper, optimization, design.

1. State of the art: structural use of basketry in construction

Parts of the following are reproduced with permission from [1]. This paper is in continuation of this work.

1.1. Wicker: culture of the raw material

Wicker is a natural fibre growing on young willows which can reach 3.5 meters height. It is cut once a year during winter. Even if it resists low temperatures and even frost, its growing prefers a mild and damp climate (Figure 1).

Figure 1: Noir de Villaine wicker fields of the basketry cooperative in Villaine-les-Rochers, France, and unbarked white wicker produced by osier du Gué-Droit.[N. Prévost]

It is a very minimal cultivation, helping to diversify the forest cover, and requiring limited inputs and maintenance. Its CO_2 emissions are marginal. The wicker production also reduces floods, silting of rivers and streams, and slows soil erosion. In the present context of climate crisis, the ecological qualities of wicker are leading a growing number of designers to question its possible use in architecture.

Nevertheless, as specified by Prévost et al. [1]: *"in France, the amount of willow plantations has drastically decreased throughout the last century, from 25 000 in 1890 to only 400 during the 1990s. The plastic revolution has led to a change in the French consumption habits and a decline in the demand for basketry products."* By providing new uses, our research is also motivated by the conservation of this craft which is currently experiencing a persistent new development in France.

1.2. Brief review of historical uses of basketry

Basketry is a craft that has emerged very early in human history, probably before the Early Neolithic (ca. 6000 B.C.) and before pottery. Basket mould prints on internal surfaces of potteries – as founded on shards dated before 8000 B.C. in Gambols Cave, Kenya – could be the first known traces of basketry.

Ancient basketry objects in museums date back to the Fayium Culture (5000 to 3800 B.C.) in the Faiyum Oasis, Middle Egypt (Figure 2). It is a fact that, quite everywhere on the planet, people have woven natural fibres for the design of objects, clothes, and even boats (Figure 3), thanks to local raw material and local know-how.

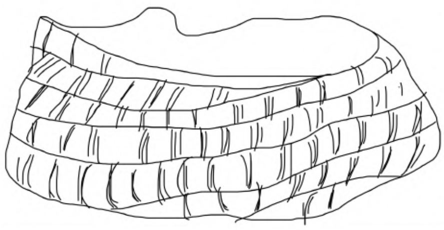

Figure 2: Sketch reproducing a circular basket of woven reed dated of Fayium Culture (original object displayed at the British Museum, object ref. EA58695).

Figure 3: Aymara (Lake Titicaca people) Totora Reed Boat at the Smithsonian Museum in Washington [John Hill]: The oldest known remains of reed boats were discovered in Kuwait and dated ca. 5000 B.C.

1.3. Basketry in the field of construction

One of the first uses of braiding in the field of construction is hedgelaying, the craft to build barriers to protect against animals by braiding the stems of a line of shrubs. Regarding the construction of shelters, it should first be noted that, as always, human beings have principally imitated techniques already mastered for a long time by animals (Figure 4).

Figure 4: Examples of weavings in nature: social republicans [D. Delso, delso.photo, License CC-BY-SA and M. Bento and H. Guidou], caciques [T. Deville] and weaver ants [Frawsy Eklablog & B. Dupont].

We find applications of basketry in primitive or vernacular habitats as, for example, in Ethiopia, in the Guge Mountain, where the members of the Dorze tribe build their dwellings by weaving ogive-shaped huts with palms of false banana trees on frames of bamboo and local wood (Figure 5). The lightweight structure can be lifted and relocated by a group of three or four people. They are initially built higher above the ground (around 10 to 12 meters) due to the presence of termites, which gradually consume the base of the huts, causing their height to decrease over time! This habitat can last for 60 to 80 years.

Figure 5: Chencha village huts (Dorze people) [Kevin Smith], and Lake Turkana huts [Eric Lafforgue, Bjorn Svensson, Alamy and Richard & Martha Shaw].

Nevertheless, in these examples, braiding is only used as a filling element on a wooden structure.

In the Iraqi marshes, the Madan people build the mudhif, a traditional reed house. The strands are braided and assembled to form compact columns or arches (Figure 6). If the structure of the building is made entirely of reeds, it remains on a "frame & filling" model. The object of our research is different since we seek the continuous and homogeneous structural design of the shell.

Figure 6: A Marsh Arab mudhif [Hassan Janal U.S. Army Corps of Engineers - U.S. Army Corps of Engineers Digital Visual Library].

Figure 7: Porky Hefer's first nest [Deezen & Animal Farm]and Laura Ellen Bacon's braided work of art.

In contemporary architecture and art, we can mention the works of Porky Hefer (Animal Farm) such as "Weaver's Nest", or the magnificent interlaced braided shells of the artist Laura Ellen Bacon (Figure 7). If their design echoes our research by their architectural dimensions and by the absence – to our knowledge – of a load-bearing substructure, our frame is however far from it by the amount of loading that a public pavilion must take up for users.

The work of the the Institutes ITKE and ICD and of the Cluster of Excellence IntCDC of the University of Stuttgart on biomimetic and fibre composite materials led to full scale prototypes supported by a structure entirely robotically made of rolled flax fibre [3] (Figure 8).

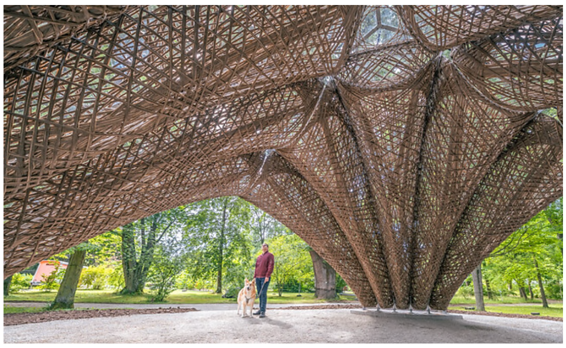

Figure 8: LivMatS Pavilion at the University of Freiburg [ICD/ITKE/IntCDC University of Stuttgart].

Our research stands out because we chose to stay in the framework of crafting techniques resulting from several thousand-year-old traditions. In order to be replicable on a larger scale, we believe that our method must remain Low Tech. Also, although the design of our shells uses modern computational techniques, they are developed with the potential to be easily manufactured by a large public.

2. Inside the BAYA algorithm

2.1. Overhaul by the example of the braided beam

As explained in [2], BAYA algorithm is applicable to any loaded surface, such as shells, as well as simpler elements like beams. This includes basketry items such as baskets. The loads circulate through the entire width of the structural surface of the shell and put it under tensile and compressive stress.

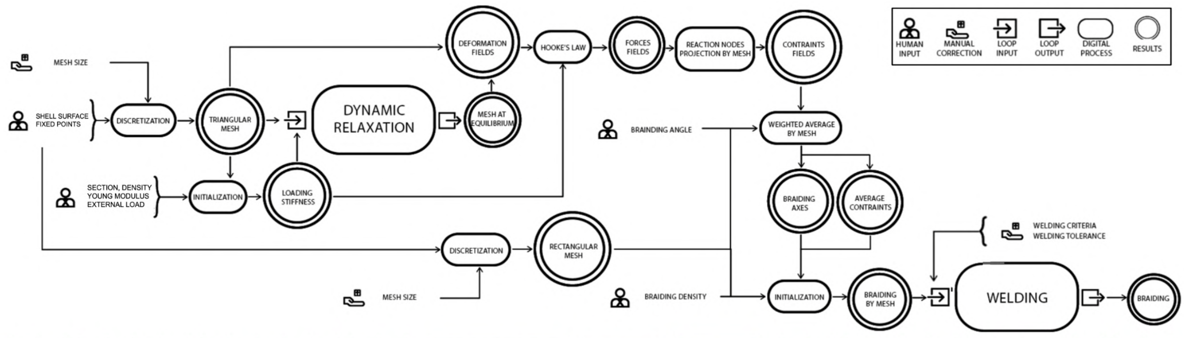

Figure 9: working flow of the BAYA algorithm [A. Breugnot].

BAYA algorithm determines the principal stresses for any shell under a given load. Thanks to optimal braiding rules described in 2.2, it is able to give the ideal braiding for the shell. Overhaul diagram is shown on Figure 9. We have chosen to illustrate its presentation on an isostatic beam on two supports loaded by a uniformly distributed force (Figure 10).

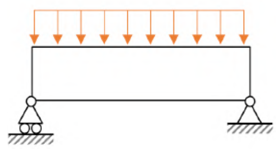

Figure 10: studied beam

1. Geometry of the studied shell: the shell surface, the position of the support points and the loads are the input data of the algorithm.

2. Finite element mesh of the shell: the surface is discretized into small rectangular isosceles triangles (Figure 11a)

3. Obtaining efforts: in the finite element edges by dynamic relaxation (Figure 11b)

4. Obtaining the principal stresses: deduced from the forces (Figure 11c).

5. Braiding of the shell: in each cell, the stems are placed to be aligned with the principal stresses and, thanks to the braiding theorical rules, the density of stems is adjusted to the need. Then we interpolate and weld the braids together. Final braiding is illustrated on Figure 11d.

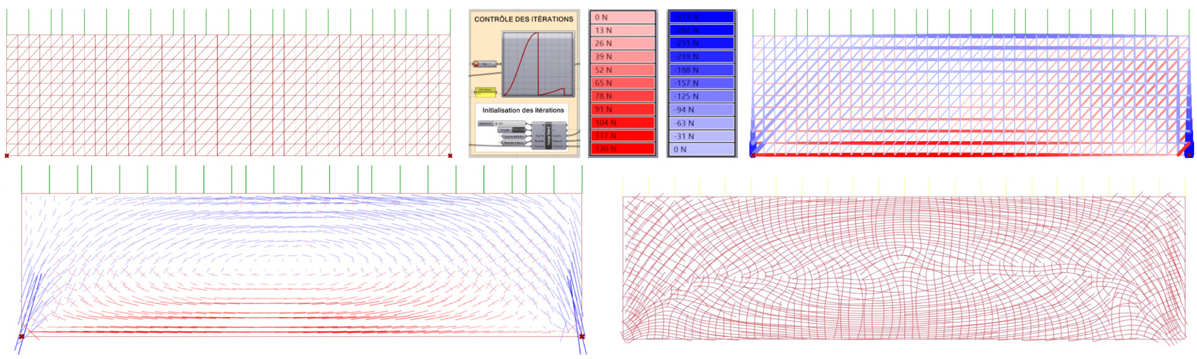

Figure 11: (a) finite elements; (b) efforts; (c) principal stresses; (d) final braiding.

The beam has been braided during a workshop at ENPC in 2024 and compared to a Pratt wicker beam. Results will be delivered in a future publication.

2.2. The rules behind optimization

2.2.1. Security coefficients

Here we look for characterizing the fact that a braided specimen, subjected to traction in one direction and compression in the other, behaves differently from a set of dissociated stems (which would then all behave in the same way). To do so, we define the traction solicitation ratio χ_T of a braided specimen as the maximum tension force in one stem divided by the average tension (total input tension divided by the number of stems). And χ_C is the equivalent ratio in compression. During numerical tests (Figure 12) we indeed observed that $\chi_T \approx 1.25$ and $\chi_C < 1.00$

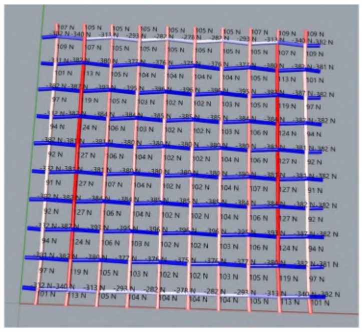

Figure 12: test specimen subjected to axial traction and compression.

This means that the tensest stem is 25% tenser than if the distribution of the tensile force was homogeneous in the braided specimen. More surprising, the second result means that part of the input compression is not found in the reaction of the compressed stems.

As first introduces in [4], the hypothesis that we are pursuing today, and which is specific to braiding, is that the deformation (slight for those observing with the naked eye) of the stems makes the mesh slightly non-orthogonal (Figure 13) and that part of the compression is transmitted in the tensed direction (thus aggravating the traction of the tensed stems).

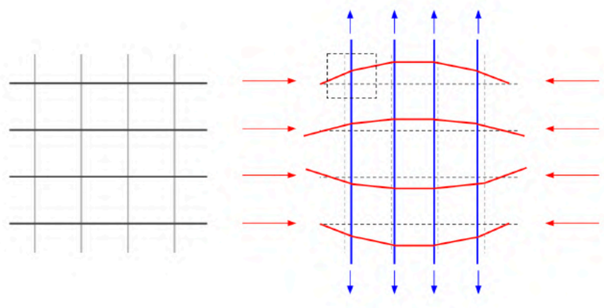

Figure 13: deformation of the specimen causing the apparition of angles [4].

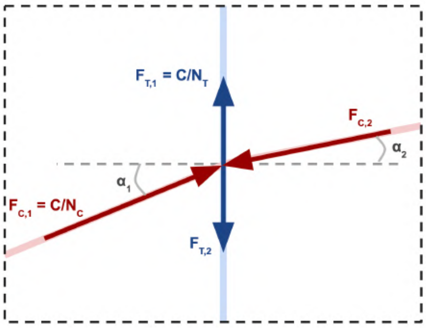

Figure 14: local notations for applying the forces equilibrium theorem [4].

Forces equilibrium over X and Y (Figure 14):

$$F_{T,1} - F_{T,2} + F_{C,1} * \sin(\alpha_1) - F_{C,2} * \sin(\alpha_2) = 0 \text{ and } F_{C,1} * \cos(\alpha_1) - F_{C,2} * \cos(\alpha_2) = 0 \quad (1)$$

$$so\ we\ have\ F_{C,2} = F_{C,1} * \frac{\cos(\alpha_1)}{\cos(\alpha_2)} \quad (2)$$

$$\frac{\cos(\alpha_1)}{\cos(\alpha_2)}\ is\ always\ between\ 0\ and\ 1 when\ 15° \geq \alpha_1 \geq \alpha_2\ hence\ F_{C,2} \leq F_{C,1} \quad (3)$$

We also can write regarding the tension:

$$F_{T,2} = F_{T,1} - F_{C,1} * \sin(\alpha_1) + F_{C,2} * \sin(\alpha_2) \quad (4)$$

$$F_{T,2} = F_{T,1} - F_{C,1} * \sin(\alpha_1) + F_{C,1} * \frac{\cos(\alpha_1)}{\cos(\alpha_2)} * \sin(\alpha_2) \quad (5)$$

$$F_{T,2} = F_{T,1} + F_{C,1} * \left(\frac{\cos(\alpha_1)}{\cos(\alpha_2)} * \sin(\alpha_2) - \sin(\alpha_1)\right) \quad (6)$$

$$\left(\frac{\cos(\alpha_1)}{\cos(\alpha_2)} * \sin(\alpha_2) - \sin(\alpha_1)\right)\ is\ always\ negative\ when\ 15° \geq \alpha_1 \geq \alpha_2\ hence\ F_{T,2} > F_{T,1} \quad (7)$$

Numerical applications for $\alpha_1$and $\alpha_2$between 0 and 15° show that χ_T ranges indeed between 1 and 1.26 and that χ_C ranges between 0.97 and 1. This hypothesis is proposed today based on recent observations. It must be confirmed in the years to come by new studies.

2.2.2. Material optimization routine

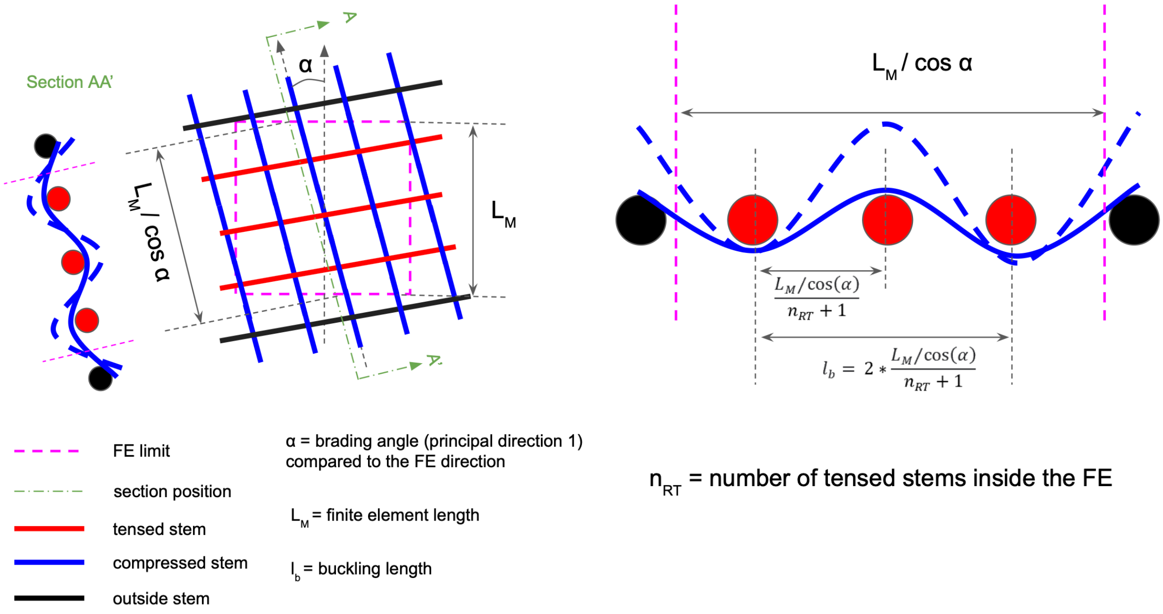

Figure 15: local notations for buckling study of the compressed stems inside the finite element. [Q. Chef and [4]].

The operating principle of our algorithm is to calculate the quantities of stems that are necessary to resist to compression and tension inputs. If the compressed stems are not enough to resist buckling, the algorithm then calculates whether it is preferable to add compressed stems or to increase the number of tensioned stems to reduce the buckling length instead. Routine is developed Figure 16 according to Figure 15 notations.

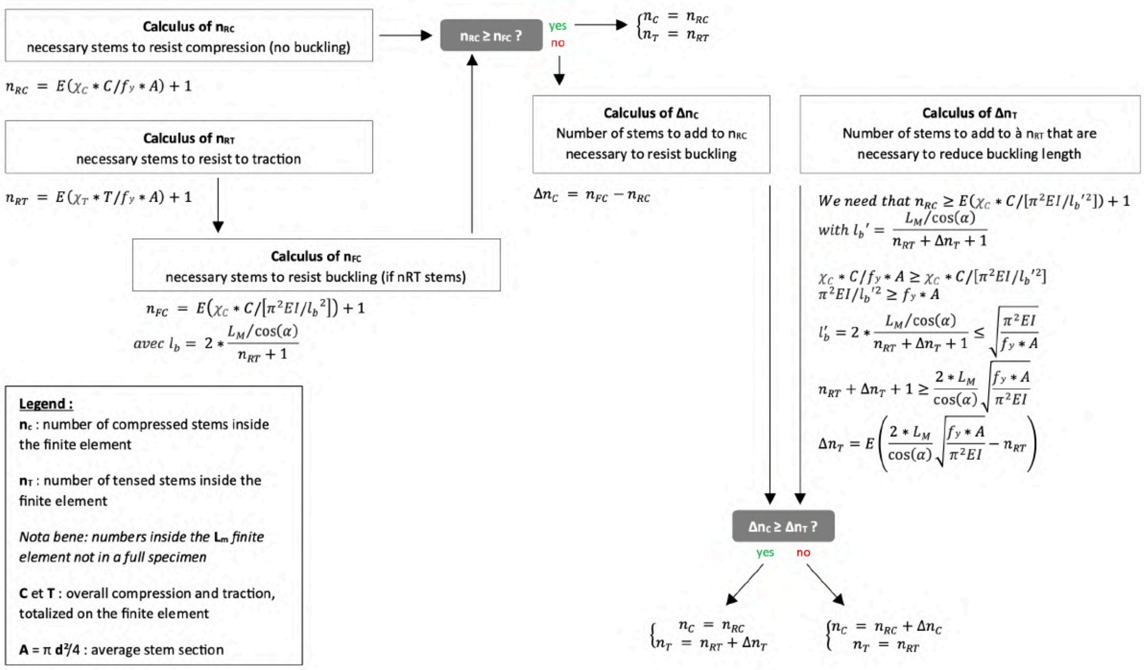

Figure 16: organigram of the rules inside the BAYA algorithm that in Grasshopper are coded in Python [Q. Chef and [4]].

2.3. Learning from experience

2.3.1. Numerical braided specimen

Our numerical simulation is conducted by dynamic relaxation. In a braid constrained in the plane, we have three types of forces: the forces due to the bending of the strands (that one must bend to pass above and then below the strands of the other layer), the spring forces related to the axial deformation of the strands (Hooke's law) and the friction forces at the nodes. More details can be found in [4].

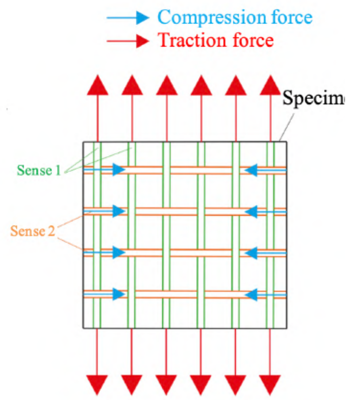

Figure 17: Diagram of a braided specimen subjected to a given stress field.

We decided to study the reaction of a braided specimen subjected to a field of principal stresses in compression and tension (Figure 17). The material, round wicker stems, is a fixed setting of the test (E, A, f_{yt}, f_{yc}). The objective is to understand the influence of the different braiding parameters listed below (Figure 18):

- The value $F_{\sigma 1}$ and $F_{\sigma 2}$ of the efforts (N/m) respectively in direction 1 and direction 2 ($|F_{\sigma 1}| \leq |F_{\sigma 2}|$).
- The braiding densities n_1 and n_2 of each layer (u/m).
- The orientation α of the braiding with respect to the principal stress field and the angle θ of braiding: angle between the two layers of braiding.

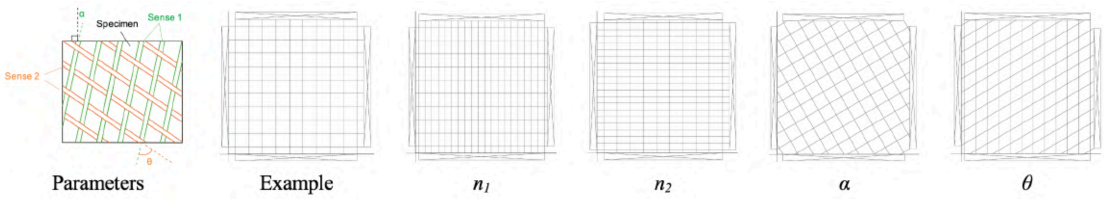

Figure 18: Input parameters on the geometry of a braided specimen

Friction forces of braiding are simulated with the introduction of a fictitious beam in the Z axis (Figure 19) with an initial length $h=2R$, R being he radius of the stems. This beam acts as a repulsive spring when $h<2R$ (friction exists) and is deactivated when $h>2R$ (loss of contact).

The study of the specimen shows us the following principles (cf. [1] for more detail):

- Global buckling (out-of-plane instability) depends mainly on compressive strength $F_{\sigma 2}$;
- Friction forces rise with $F_{\sigma 1}$ and fall with $F_{\sigma 2}$ which explains why instability failure appears with lower compression values when tension is not high enough;
- Moderate values of $F_{\sigma 2}$ lead to nodes translation or rotation, even negative friction;
- Changing the braiding angle θ has little effect if the input forces are almost parallel to the strands (α close to zero); which validates the idea of braiding along the principal stresses' directions.

The numerical model idealizes reality, and several simplifying assumptions were made for the verifications. It will be necessary to verify our outcomes by a similar experimental study.

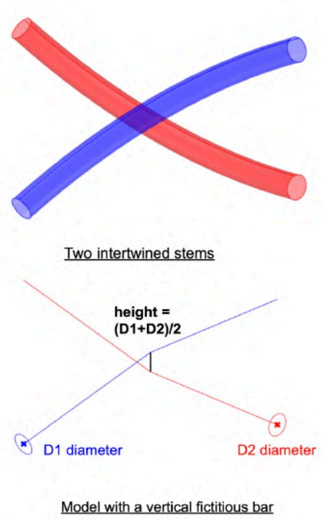

Figure 19: fictitious beam.

2.3.2. Baya Nest

The Baya project, is a human-size suspended nest in wicker [2]. It has been displayed in the park of the Butte du Chapeau Rouge in the 19th district of Paris. Before constructing at scale 1 (Figure 21), we tested our numerical model comparing its results to a 1:2 scaled physical model (Figure 20).

At both scales, the confrontation to both scales has shown that in numerous considerations, our conception with BAYA algorithm was accurate and satisfying a global optimisation of wicker quantities. Nevertheless, it also underlined two limits:

1. BAYA is able to give the deformed shape with precision, but it cannot quantify it.
2. In our DR numerical tests, the non-slipping criteria, depending on the relation between the force between the braids and the friction coefficient of the wicker is frequently not verified. Indeed, in the Baya project, we saw that the nodes are slipping at each use.

So, the lifetime of the projects is limited by this phenomenon (our projects are temporary, so this problem is not crucial here). Further studies are to be led. In the meanwhile, a solution could be to ligature a sufficient number of nodes.

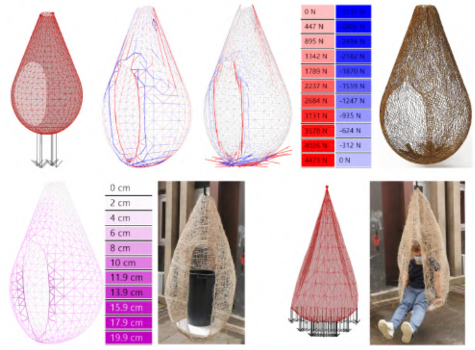

Figure 20: BAYA algorithm results on the project, displacements are compared with a 1:2 scale model.

Figure 21: Final steps during the making of the Baya project (Ø1m, h=3.3m), hanging the nest to the tree.

2.3.3. Wicker Footbridge

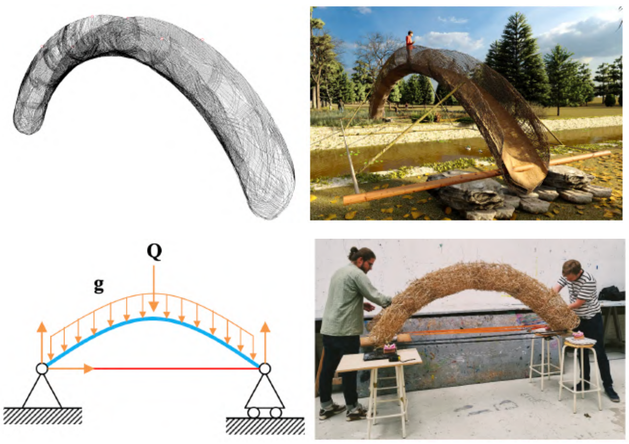

Figure 22: (a) BAYA final braiding, (b) 3D artistic view, (c) static scheme, (d) 1:5 model

We built another scale 1 object with BAYA, this time in compression: a 12.8-meter-long wicker footbridge forming an arch (Figure 22). This footbridge has been designed by Nicolas Prévost and Marc Leyral *(Construire l'Architecture, ENSAPLV)* for the 1st edition of the *Utopies Constructives* festival which will take place in spring 2024 in the city of Richelieu (Indre-et-Loire, France). The festival is organized by the BETA and la Teinturerie, in partnership with la Maison de l'Architecture Centre-Val de Loire. Construction was carried out with the participation of the Duperré, Boulle and Oliver de Serres and the École Zéro during two successive workcamps.

It has been finished by Séverine and Patrick Boyer (Osier du Gué-Droit) with Pierre Abernot and Matthieu De Grégorio. Like the nest, the footbridge has been studied at a smaller scale (1:5) before scale 1. This new confrontation underlined two new possible improvements:

1. BAYA is able to predict local buckling but not the global buckling of the shape.
2. In order to be easily used, BAYA needs to improve its outputs in term of execution plans.

Detailed explanation of the conception, calculus and fabrication of the footbridge can be found in [1].

3. New application: *Semaine Design* benches

3.1. Context

In 2023 and 2024, The École Nationale des Ponts et Chaussées ParisTech invited our research team to participate to *La Semaine Design*. It is a one-week workshop that gather engineering students from ENPC with architecture students from ENSA Paris-Est and design students from Penninghen. The aim is to collaborate to design, calculate and build an object that showcases a building engineering technique.

We proposed to groups of 7 students each to design and build in only 4 days a 100% wicker bench of around 2,2m span (Figure 23). Benches are all-in-one structures that oblige the designer to deal with flexion (the deck), compression (the piers), global stability as well as esthetics and ergonomics.

Figure 23: Benches at ENPC in 2023: (a) *Pringles*; and 2024: (b) *La Vague,* (c) *Banché,* (d) *Bubble*

Goal: Students are invited to freeform their bench on Rhino then to use the BAYA algorithm to model the structural behavior of the surface. For a given load (4 distributed forces for a total of 80kg), they obtain forces, stresses, optimal braiding plans and deflection (in shape, not in value). They have no limit in the use of material since the aim is to have the best load capacity and to show faithfulness to BAYA results.

Construction method: Based on section cuts in Rhino, the students make a temporary OSB skeleton of their shape. The skeleton is covered with a 15-20cm wide "wicker mesh". Once the mesh is covered with enough material, the shape is rigid enough to demolish the OSB and withdraw it.

3.2. Tools developed to ease faithful braiding

The Baya Nest and the Wicker Footbridge were built based on the final braiding output (with interpolated connected stems visuals). Studying the principal stresses diagram and analyzing the behavior of the small-scale study helped to underline the most important parts of the braiding but this approach produced difficulties to match algorithm results with the real object manual braiding.

In 2023 for Pringles: To avoid that, we first proposed to use "braiding plans". For each cell of the discretized shape, users can print a 2D local plan that contains directions and density of the braiding (Figure 26). Results were better but it was still hard to localize and orientate the plans on the mesh.

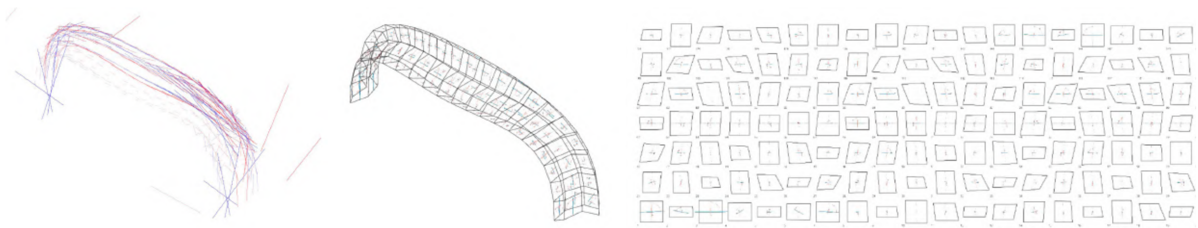

Figure 24: For *Pringles*: (a) principal stresses, (b) braiding plans on the 3D shape, (c) printable 2D braiding plans.

In 2024 for La Vague: A completely new technique was developed (Figure 25). One must match the size of the physical mesh with the one used in BAYA. Then the physical mesh is painted, and cells numbers are marked. In BAYA one uses density dilters to highlight strong paths of braided material inside the structure, repeating the operation 3 times for each direction. In this way, instead of braiding a medium density everywhere then to increase density in the most stressed regions (which requires strength and technique) one starts with dense path first, with the advantage of using continuous stems.

Figure 25: For *La Vague*: (a) one step of braiding needs during the filter operation, (b) braided shell after this step, (c) zoom on braiding plan, (d) wicker mesh in orange and cells number marks.

3.3. Results, conclusion and openings

In 2023, *Pringles* bare 110kg additional load with the use of 60kg of wicker (Figure 23a). In 2024, *La Vague* bare 115kg additional load with the use of 40kg of wicker (Figure 23b).

Benches are calculated for 100kg but, with a 1.50 ULS coefficient and a 3.8 material coefficient, we never observe the failure because the deflection under one or two young adults' weight are already high. Moreover, for easier manipulation during a short-time workshop, we used "fresh" wicker instead of withe wicker (which is bark and dry) so the Young Modulus is very low. To overcome deflection and reach resistance failure, we should use white wicker and avoid node slipping with ligatures. Be able to calculate the deflection and add a SLS design criteria is crucial for future BAYA improvements.

We also observed that modelling the 3D shape is time consuming and require skills that some users don't have. Replace surface input in BAYA with mesh input or 3D-scans could be useful.

Acknowledgements

Cyril Douthe from ENPC Paristech, our co-supervisors Laune Néron, Orlane Guillouet-Lamy, Héloïse Douin and all the students of la Semaine Design especially those whom work is showcased in this article: *Pringles* in 2023 (Margot Demoustier, Miléna Herrouin, Mathieu Carriere, Kyrylo Rannyev, Eray Yesil, Soleil Naud, Camille Bruhat, Marie Devaux, Xueyao Wang) and *La Vague* in 2024 (Elisa Lima, Garance Badoil, Antoine Jeanselme, Sinclair De Kerautem, Violette Dupuis, Chloé Gicquel, Floriane Pannetier). The ENSAPLV, the AMP research unit, Professor François Guéna (Scientific Director of the MAP-MAACC laboratory), Pierre Jehel from CentraleSupélec, Albin Breugnot.

References

[1] M. Leyral, Q. Chef, M. Hymans, "Baya Project: building structural shells in wicker" in Journal of the International Association for Shell and Spatial Structures, 2023.

[2] M. Leyral, C. Chef, P. Guerold, S. Ebode, "The Baya Nest pavilion project: braided pattern optimization for hanging shell structures by dynamic relaxation," in *Inspiring the Next Generation - Proceedings of the International Conference on Spatial Structures 2020/21 (IASS2020/21-Surrey), Edited by: Alireza Behnejad, Gerard Parke and Omidali Samavati, published by University of Surrey, Guildford, UK, August 2021*

[3] M. G. Pérez, Y.Guo, J. Knippers, "Integrative material and structural design methods for natural fibres filament-wound composite structures: The LivMatS pavilion," in *Materials & Design, Volume 217, May 2022*, 110624

[4] M.Leyral (2023). "Du souple vers le raide: évolutivité entre les phases de construction et de service des structures de couverture et de franchissement en fibres végétales et en bois. Conception et fabrication issues de la confrontation de résultats expérimentaux sur modèles réduits aux modèles numériques par relaxation dynamique." Ph. D. Thesis. CNAM, Hesam.

BAYA algorithm is available on our website *www.construire-l-architecture.com*