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### ► **To cite this version:**

Nicolas Prevost, Marc Leyral, Marc Hymans, Albin Breugnot, Quentin Chef, et al.. Building crossings in wicker: flexible construction of a postformed footbridge in active bending stiffened during service phase. IASS Annual Symposium 2022 & the 13th Asian-Pacific Conference on Shell and Spatial Structures: Innovation, Sustainability and Legacy, Sep 2022, Beijing, China. hal-03882279

**HAL Id: hal-03882279**

**<https://hal.science/hal-03882279>**

Submitted on 2 Dec 2022

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## **Building crossings in wicker: flexible construction of a post-formed footbridge in active bending stiffened during service phase**

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### **Abstract**

The first traces of basketry date back to the Sumerian's period (4000 years BC). From now on, these braiding techniques have been used to craft vernacular shelters, clothes, furniture and tools. However, they are uncommonly used in architecture and are generally limited to non-structural filling elements. To our knowledge, the Baya project developed in 2020-2021 at ENSA-Paris-la Villette and CentraleSupélec schools was one of the first examples of a braided wicker structural shell in architecture. Based on the braiding optimization algorithm developed during this previous project, our research intends to question one step beyond: crossings. This innovative research is demonstrated by the realization of a 12.8-meter-long footbridge for the *Utopies Constructives* festival in Richelieu's Park. The footbridge, which echoes the reed boats of the Uros, a Peruvian tribe, will be braided flat before being moistened and shaped by buckling; then it will be stiffened post-buckling by braiding the railings together. Building in a flexible way, then stiffening during the service phase is both the constructive process of elastic gridshells and the one used by basket weavers who braid the green wicker, which then stiffens once the object is formed.

**Keywords:** Footbridge, wicker, dynamic relaxation, form finding, elastic bending, earth mortar

### **1. Introduction**

Wicker is a natural fiber, collected once a year during winter. Its height can reach 3.5 meters. It is produced by young willow cuttings. It grows in the climates encountered in Metropolitan France. It resists low temperatures and even frost.

It's a very minimal cultivation, requiring limited inputs and maintenance, which makes it possible to diversify the forest cover. Its water consumption and its CO<sub>2</sub> emissions are low (wicker is also capable of storing carbon, but the quantified evaluation of this benefit depends directly on the life span of the object that is made with). The wicker production also reduces floods, silting of rivers and streams, and slow soil erosion. At the dawn of the climate crisis, the ecological qualities of wicker are leading a growing number of designers to question its possible use in architecture.

Nevertheless, 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. The department of Indre-et-Loire, where our project is realized, undertakes actions for the conservation of this craft.

Basketry is a craft that has emerged very early in human history. The first traces of wicker objects date back to the Sumerian civilization (4 000 BC) and the first traces of basketry were found in Fayum in Upper Egypt, around 10 000 BC. Everywhere on the planet, people began to weave natural fibers for the design of objects, clothes, or shelters, thanks to local raw material and local know-how.

Architecture and construction have slightly opened their doors to the art of wickerwork, but it is mostly limited to non-structural filling. Porcky Hoeffler, particularly, with the construction of woven huts, conceptualizes the designs of crossing, somewhere between timber skeleton and wicker. To continue this path, a team of students and teachers from ENSA Paris-la Villette and CentraleSupélec has been developing the BAYA project since 2021: an algorithm created to optimize the braiding of structural shells for architecture.

As a demonstration, a suspended nest has been created with this algorithm [4]. Our research is a continuation of this project: indeed, we will use the BAYA algorithm to cross long spans with wicker, and we will try to improve this tool thanks to this new feedback. Laura Ellen Bacon produces large-scale artistic objects, including relatively long-span crossings, but these are not intended to support any external load such as the weight of users. Finally, one of the best examples of braided wicker crossings is found among the Uros people in Peru, with their boats made of totora, the local rush (in case of rough sea, the boat is not supported by the water in its entire length and must therefore be able to resist bending).



Figure 1: Porcky Hoeffler's project, Baya nest [4], Uros' boats [Vittorio Carlucci], Laura Ellen Bacon's project.

These observations naturally lead us to question the feasibility of a crossing for architecture, using a construction method derived from wickerwork. In our methodology, which we will detail later, proof will be the answer to that question, since we propose the construction of a wicker footbridge with a span of almost 13 meters.

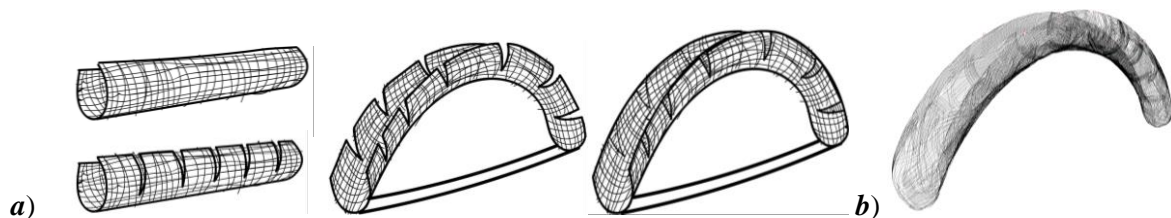


Figure 2. Construction phasing of the footbridge (a) and optimal wicker braiding designed by BAYA (b)

## 2. Crossings with a wicker footbridge

### 2.1. Qualitative approach: obstacles to the design of a crossing made of braids

Thanks to our interviews with designers and basket makers, to the available literature and to the Baya nest project's feedback, we managed to identify the following obstacles to our crossing project:

- **Durability:** like timber, wicker is sensitive to UV, moisture, fungal and wood-eating insect attack. Moreover, the small cross-section of the stems maximizes the exposed surface in relation to the volume of needed material, which makes the plant fibers even more sensitive to their environment. Solutions do exist - essentially the same as for timber: heat and/or autoclave treatments - but to date we do not have enough feedback on the durability of these fibers when used in architecture, and even less if they are left outdoor and unprotected.
- **Evolvability of the material:** like timber, wicker and plant fibers creep. However, there is few information about it. For Baya, for example, we extrapolated the creep of timber onto wicker without really knowing the impact of this hypothesis. Furthermore, wicker is soft when green (or soaked) and becomes stiff when dried: an advantage for basketry since braiding requires handling a soft material and the object designed often needs to have sufficient stiffness for its use. However, as it dries, the wicker also becomes more "brittle". We do not yet know the impact of this characteristic to evolve on a structure bearing short and long-term loads.
- **Node slipping:** This is the main feedback from the Baya project. Despite the numerical experiments that allowed us to create this design tool, the nodes of the full-scale project were slipping at each use, causing deformation of the structure under load/unload cycles. This reaction could be described by the term "fatigue creep", although it is obviously due to different reasons from those that cause these two phenomena: creep is the deformation of a structural element subjected to a long-term loading. In our case, we deal with load/unload cycles (hence the parallel with "fatigue") caused by a short-term variable load. A "hysteresis cycle of deformation by slipping" is certainly a more accurate term to define the phenomena.
- **Lightness:** here again, a characteristic that may at first appear to be an advantage. However, when crossing with an arch, for example, one wishes to limit the deformation of the funicular under variable loads. In fact, if the funicular comes out of the arch, the section decompresses and the masonry arch collapses. For this purpose, the arch is usually designed in such a way that its self-weight (and any additional dead loads) is significantly dominant over the live loads. Then the lightness of wicker would be a handicap for this type of design. However, the capacity of wicker to resist traction makes a significative difference between masonry arches and ours, when subjected to live loads located in specific positions. This important issue will be developed later in the article.

### 2.2. Development of a braided wicker footbridge project

#### 2.2.1. Project background

To contextualize our research, we designed a footbridge for the 1<sup>st</sup> edition of the *Utopies Constructives* festival which will take place in spring 2023 in the city of Richelieu (Indre-et-Loire, France). It is organized by the BETA and la Teinturerie, in partnership with la Chancellerie des Universités de Paris and le Campus des Métiers d'Art et du Design.

For this occasion, our team of students from ENSA Paris-la Villette and CentraleSupélec with teachers from *Construire l'Architecture* have designed one of the two footbridges that will be exhibited. Built in wicker and with a span of 12.80 meters, this construction was carried out with the participation of the Duperré, Boule and Oliver de Serres art schools during a workcamp supervised by the BETA and la Teinturerie, helped by wickerworkers from the oseraie de Gué-Droit.

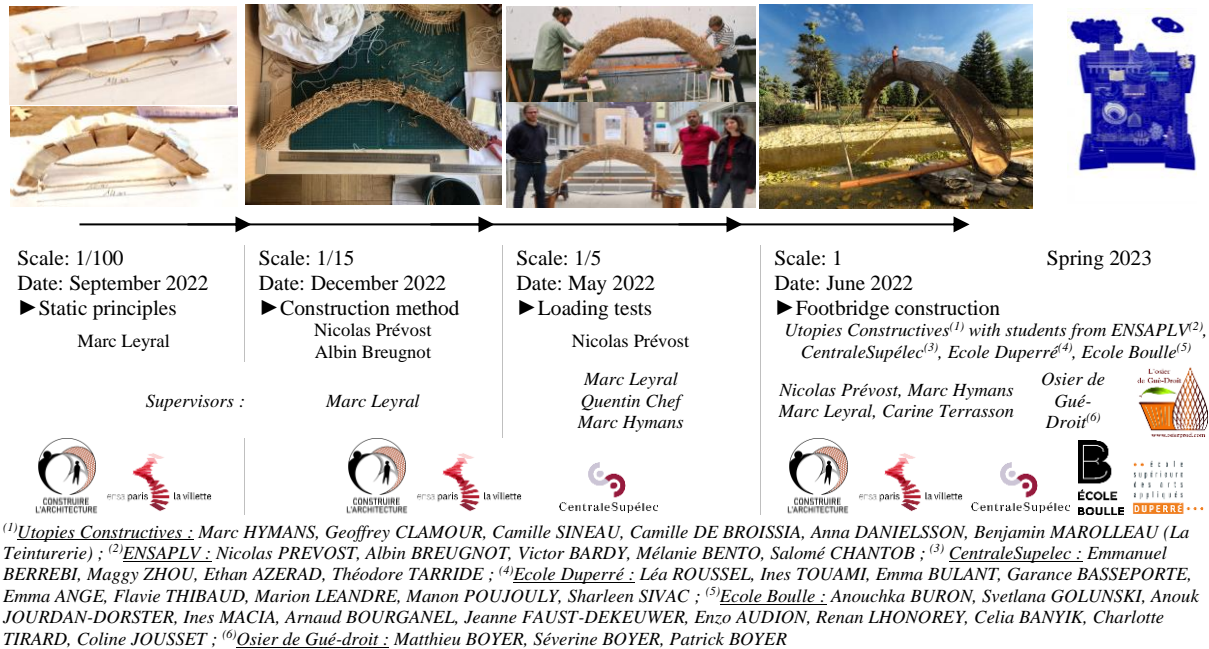


Figure 3: Timeline of the project's design and construction; participation of the different contributors.

Recreating an architectural walk path around the old site of the castle, the project is set in an exceptional site. In the park of more than 475 hectares, which was an integral part of the Cardinal de Richelieu's castle (dismantled during the 19th century), the project takes place over a moat. In this site, which combines nature and tranquility, old moats cut the park into geometric shapes. They banks cannot bear horizontal load, which constrains the choice of the structural typology of the footbridge. In this context, and to respect our site, the keywords of the project are frugality and low-tech.



Figure 4: Project site.

### 2.2.2. General construction method

The execution of the footbridge is based on the construction of post-formed elastic gridshells:

1. The object is first made (by braiding the wicker) flat and flexible  
► In our case, the footbridge is braided flat from wicker and the railings are regularly split in order to drastically reduce the bending stiffness of the deck.
2. It is then shaped by buckling  
► The ropes connecting the legs are put under tension, compressing the footbridge deck, which begins to buckle.
3. Once in its final shape, it is stiffened for the service phase  
► The interruptions in the railings are stitched together, forming a structural U shape one meter high by one meter wide.

In its service phase, the bridge works like a bowstring bridge (unless one walks directly on the arch). The arch is compressed by its self-weight and the loads of the users. The horizontal reaction generated at the supports is balanced by the traction in the ropes that were used to shape the arch in its assembly phase. This allows the footbridge to be raised onto land before being pushed over the moat. To limit the knots slipping observed on Baya, horizontal bamboos are inserted between the strings to increase tension, hence applying pre-compression to the bow.

Ultimately, anti-lateral buckling elements are added between the ropes and the deck as explained below. We will discuss later whether the deck should be weighted with clay soil.

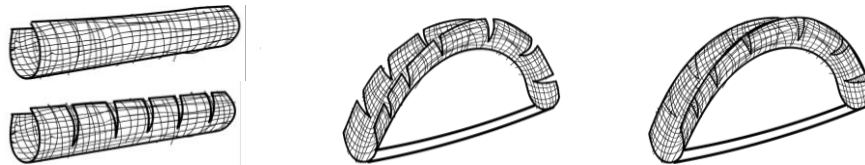


Figure 5: Construction phasing of the footbridge (before adding anti-buckling elements).

From a logistical point of view, instead of cutting the railings, we chose to prefabricate the bridge off-site in six sections, which are easier to transport. Then we assembled the flat pieces together by sewing the center part (the deck), leaving the future railings open in the first place.

Now the overall shape of the project, its static diagram and its construction method have been defined, the braiding of the arch forming the deck must be designed. To do this, we used the BAYA algorithm, which is able to draw the optimal braiding of any shell for a given load.

### 3. Initial conception using numerical models

#### 3.1. BAYA: structural shells design and optimization algorithm for the architecture

This chapter is quoted and adapted from [4] with the permission of the authors.

BAYA algorithm is applicable to any loaded surface, such as shells, as well as simpler elements like beams. These elements constitute the entire structure of the project. The loads circulate through the entire width of the structural surface of the shell and put it under tensile and compressive stress.

After observing the behavior of the stems, on a 30\*30 cm specimen, we defined the relation between the geometrical characteristics of the braid and its mechanical behavior when it is subjected to a given loads field. This output fed the algorithm BAYA, capable to calculate the principal stresses of any shell under various loading cases and to give its optimal braiding.

##### 3.1.1. The laws of optimal braiding

Methodology: our numerical simulation is conducted by dynamic relaxation, a method that allows us to solve static equilibrium problems by a fictitious dynamic calculation. Bouhaya [1] explains that the objective is to find the equilibrium position of a structure subjected to a set of loads by a pseudo-dynamic calculation : “it is an iterative method that describes the movement of the structure from the moment of loading to its equilibrium [...]” and, “according to [Barnes], “the basis of the method is to trace step-by-step for small time increments,  $\Delta t$ , the motion of each node of a structure [from an initial disturbed instant] until, due to artificial damping, the structure comes to rest in static equilibrium.”

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 knots.

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

- The value  $F_{\sigma 1}$  and  $F_{\sigma 2}$  of the efforts (N/ml) 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/ml).
- The orientation  $\alpha$  of the braiding with respect to the principal stress field.
- The angle  $\theta$  of braiding: angle between the two layers of braiding.

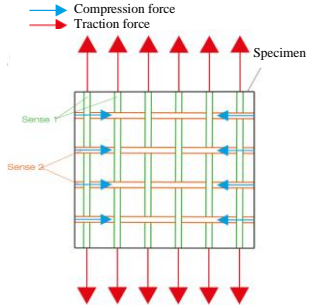


Figure 6: Diagram of a braided specimen subjected to a given stress field.

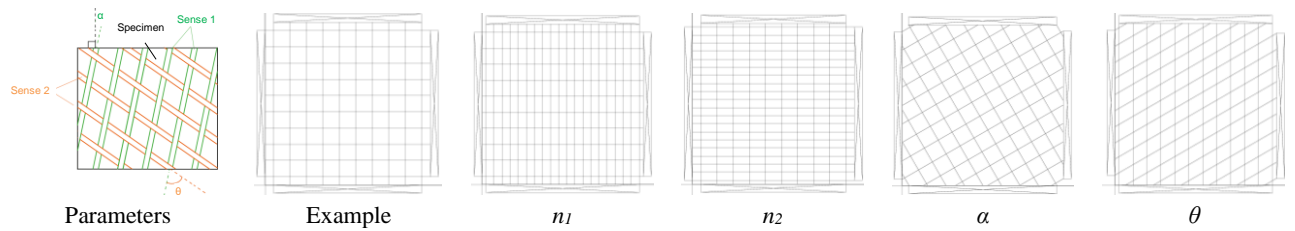


Figure 7: Input parameters on the geometry of a braided specimen.

The study of the specimen shows us the following principles (cf. [4] for more detail):

- As expected, the yield ratio  $T_{max} / (A * f_{yt})$  is a linear function of the tensile strength  $F_{\sigma 1}$
- Local buckling ( $C_{max}$  compared to Euler's force) is not an issue with regular  $n_1$  and  $n_2$  densities
- Global buckling (out-of-plane instability) depends mainly on compressive strength  $F_{\sigma 2}$
- Friction forces raise 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
- High values of  $F_{\sigma 2}$  lead to knots translation or rotation, even negative friction (decompression)
- Positive friction force possesses a physical limit (depends on the diameter of strands)
- Changing the braiding angle  $\theta$  has little effect if the input forces are almost parallel to the strands ( $\alpha$  close to zero); which validates the idea of braiding along the principal stresses.

### 3.1.2. BAYA algorithm for optimal braiding of architectural shells

The BAYA algorithm determines the principal stresses for any shell under a given load. Thanks to the above optimal braiding laws, it is able to give the ideal braiding for the shell. The algorithm can be applied to any loaded surface, including basketry items such as baskets, we have chosen to illustrate its presentation on an isostatic beam on two supports loaded by a uniformly distributed force.

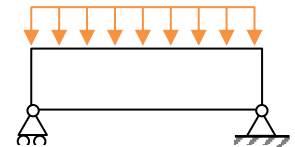


Figure 8: Static scheme of the braided example.

1. Geometry of the studied shell: The shell surface, the position of the support points and the loads are the input data of BAYA algorithm.
2. Finite element mesh of the shell: The surface is discretized into small rectangular isosceles triangles, each representing a finite element of it.
3. Obtaining efforts: in the finite element edges by dynamic relaxation.
4. Obtaining the principal stresses: deduced from the forces by rotation of stresses' coordinate system on the largest support reaction of the right-angled isosceles triangle.
5. Braiding of the shell: by using the laws defined above.

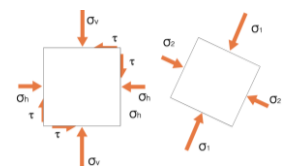


Figure 9: Principal stresses on a finite element.

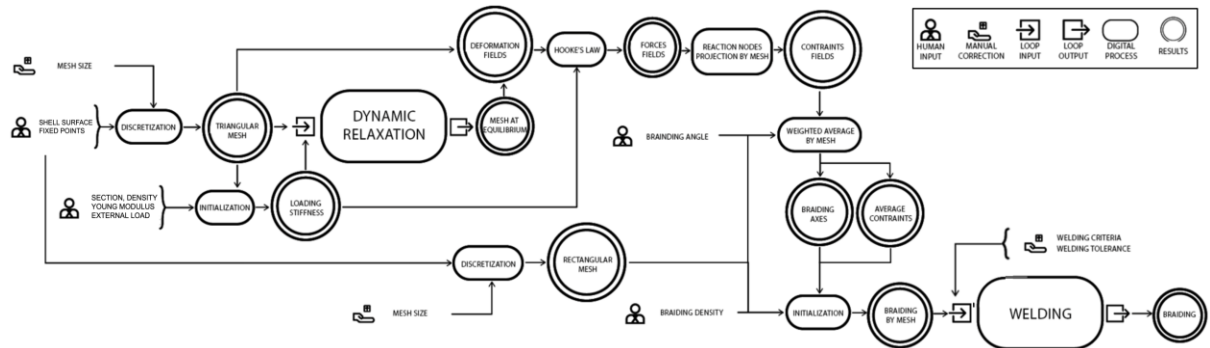


Figure 10: Functional diagram of BAYA algorithm.

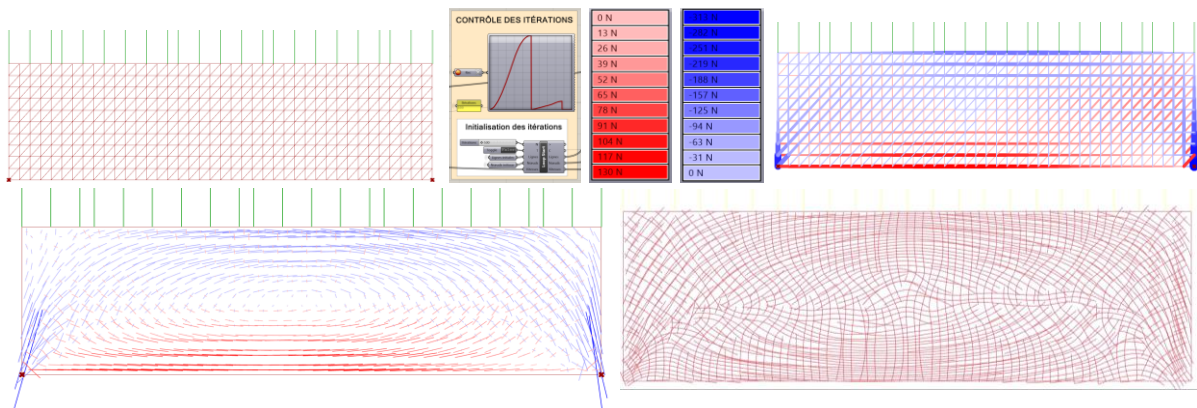


Figure 11: Meshing, strains and principal stresses, and optimal braiding by BAYA for the given example.

### 3.2. Application to the wicker footbridge

During the construction phase, the deck functions as a gridshell and thus has an elastica shape. During the service phase, it functions as an arch under a quasi-distributed load, so the ideal shape is rather the inverted catenary one. The shape of a hanging chain (hyperbolic cosine) only depend on its axial stiffness and the elastica shape of flexible rod depend both on its axial stiffness and on its bending stiffness. Nevertheless, bending stiffness is negligible compared to the axial stiffness. This is what Douthe [2] argues : *“the stiffness of the shell comes from its shape and that this shape has been specially studied to take up the dead weight loads by membrane stress, i.e. only by axial forces in the gridshell elements. However, (...) the material resists well to axial forces (much better at least than to bending forces), the dimensions of the gridshell elements can therefore be reduced (...). This reduction in cross-sections is accompanied by a decrease in inertia so that the bending stiffness of the elements is low, which legitimizes retrospectively the initial hypothesis and the form finding using a net model.”*

Based on his work, we know that the elastica shape almost functions as a funicular if the angle of attack  $\alpha$  is less than  $65^\circ$  (optimum at  $57.5^\circ$ ), corresponding to a  $pL^3/EI$  ratio below 65. We retained this value for the design of the footbridge. The overall shape of the arch resolved, we had now to use BAYA algorithm to predict an optimal braiding pattern for the deck (for the service phase).

The load is bore by the U-shaped deck; the whole structural thickness is thus put under stress. To calculate complex rounded shapes, the algorithm simplifies the surface into a mesh of simple

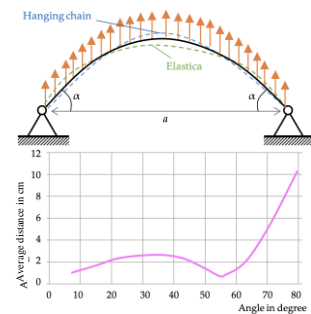


Figure 12: Diagram of the problem studied by Douthe, and evolution of the distance to the hanging chain form with the angle  $\alpha$ .



geometric shapes. BAYA gives the braiding of these finite elements, the density and orientation of the strands according to the value of the stress and its orientation in these finite elements. Let us note that, density can be reached in plane or in thickness, which could change the structure's rigidity.



Figure 13: Optimal braiding of the bridge according to BAYA (the real diameter and number of strands have been reduced for a better reading) and corresponding 3D insertion (with the anti-buckling bamboos).

#### 4. Confronting experiment with construction

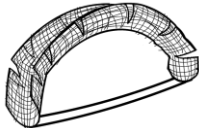
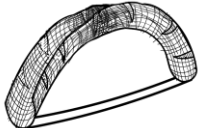
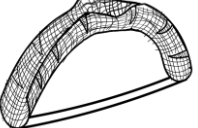
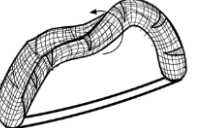

Once we managed to demonstrate the constructive feasibility on small-scale models, we compared our structural design to the results of our experiment: this step is necessary because BAYA does not take into account a certain number of parameters such as node slipping, buckling and overturning, and the calculation of the deflections. Therefore, we built a 1:5 scale model. The tests that followed brought us two very significant benefits:

1. A real checking of the structural feasibility of the footbridge project, its resistance and the improvements that could be done.
2. Tangible feedback of the BAYA algorithm and a collect of some data in order to make corrections and improvements, for instance data on the previously mentioned parameters that are not taken into account yet.

##### 4.1. Structural failure modes

In order to develop a methodology for experimental analysis, we have to anticipate the structural failure modes that could ruin the footbridge. We have selected five of them in the first instance:

Table 2: The footbridge expected failure typologies.

				
<b>M1 Failure</b> <i>Wicker failure by traction</i>	<b>M2 Failure</b> <i>Wicker stress failure by compression.</i>	<b>M3 Failure</b> <i>Local wicker failure by buckling</i>	<b>M4 Failure</b> <i>Failure by global buckling.</i>	<b>M5 Failure</b> <i>Ropes failure by traction.</i>

**M1**, **M2** and **M3** failure modes are normally taken into account by BAYA. We have calculated them with a maximum load equivalent to the weight of four people on the real scale footbridge. It is important to point out that these failure modes are very sensitive to the variations of the position of the funicular in relation to the neutral fiber of the section. Indeed, if the line of thrust, representing the normal force  $N$  in the arch, is offset comparing to the neutral fiber of the arch sections, a bending moment  $M$  appears in relation to it. Depending on its position, it can considerably increase the compression of the arch, but it can also locally cause traction.

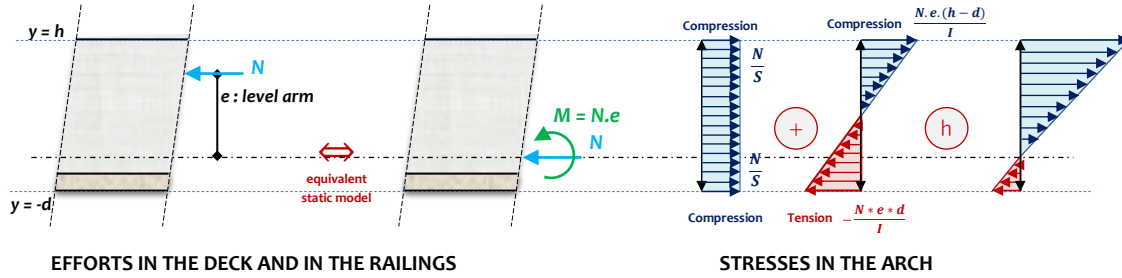


Figure 14: Additional force  $N + M$  in the arch coming from the eccentricity of the pressure curve with respect to the neutral fiber position and stress diagram in the U-shaped section.

Considering the low flexural stiffness of the deck – due to the material and the braiding – the **M4** failure mode appears critical. However, BAYA, in the design of the ideal braid, only takes in consideration local stresses and not the global instabilities. This failure mode was not numerically anticipated and the results of the model tests will therefore be of considerable help in this respect.

A quick calculation shows that the **M5** failure method is far from the conditions of use. However, to be conservative, we will add redundancy by doubling the ropes.

#### 4.2. Research methodology

In this static scheme,  $Q$  is the punctual load of the users on the footbridge placed in the middle of the arch (less favorable than in the numerical analysis) and  $g$  is the distributed load of the footbridge's own weight, including any dead weight from the clay soil we may add on the deck.

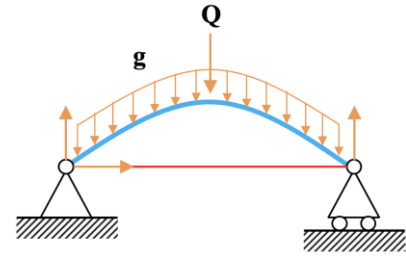


Figure 15: Static scheme of the footbridge in service.

In a masonry arch, the maximum risk of failure generally comes from a variable heavy and punctual load, as stated by Édouard Méry [5], a Ponts et Chaussées engineer, in the first half of the 19th century: “When a heavy load is made to pass over a vault, the line of thrust successively takes on various forms, as would a suspension chain, and while it undergoes these oscillations, it must always remain enclosed between the intrados and extrados of the vault so that the latter does not fall.” Once again, comparing a wicker bridge to a masonry arch has obvious limits but is a good place to start.

Consequently, in order to minimize this risk, the variable load must not exceed a certain proportion of the distributed load, that we initially set at 50%. This means that for a permissible load  $Q$ , an equal dead weight must be distributed on the footbridge. If  $L = 12.80\text{m}$  is the span and  $L_a = 14.80\text{m}$  is the total length of the arch of the footbridge (length of the spring line), we then have:  $Q = g \cdot L_a$

##### 4.2.1. Upscaling the assessed parameters

- 1) Scaling of the stress. The maximum stress on the bridge is  $\sigma = \frac{M \cdot y}{I}$  with  $M = \frac{g \cdot L^2}{8} + \frac{Q \cdot L}{4}$  where  $M$  is the bending moment.

Thus, the stress of a 1:1 scale footbridge under a given load is the same as that of a 1:5 scale bridge under a load 5 times smaller because  $5 \cdot 5^2 \cdot 5 / (5^4) = 1$

- 2) Scaling of the deflection.

The maximum deflection in an equivalent beam is  $d \approx \frac{5 \cdot g \cdot L_a \cdot L^3}{384 EI} + \frac{Q \cdot L^3}{48 EI}$ .

Thus, the deflection/span or deflection/rise ratio of the 1:1 scale footbridge under a given load are the same ratio of the 1:5 scale model under a load 5 times smaller because  $5 \cdot 5 \cdot 5^3 / (5^4) = 5$

#### 4.2.2. Principle of loading and evaluation of the model

We want to know how many people weighing 80 kg maximum could stand on the 1:1 project. Let us recall that, for each person, the same amount of dead weight shall be added to the footbridge.

Table 3: Planned loading tests and equivalence for extrapolation of results to scale 1.

Number of people		1	2	3	4	5	6
Footbridge loading Scale 1:1	$Q$ (kg)	80	160	240	320	400	480
	$g$ (kg/m)	5.4	10.8	16.2	21.6	27	32.4
Footbridge loading Scale 1:5	$Q$ (kg)	16	32	48	64	80	96
	$g$ (kg/m)	5.4	10.8	16.2	21.6	27	32.4

The physical model will be loaded in approximately 4kg increments of  $Q$ . The deflection at the center of the bridge is measured at each increment. At 12kg the bridge will be fully unloaded, and the deflection measured (residual amount of deflection is then evaluated). The loading will continue in the same way until failure. A second test is carried out without distributed additional loads.

#### 4.3. Results and analysis

The results of the first two loading tests are given in the table below.



Figure 16: Braiding and loading tests on the 1:5 model.

Table 4: Results of the first loading tests (without anti-buckling).

Loading test 1	$g$ (kg)	4.6*	4.6	8.7	8.7	12.8	12.8	4.6	16.08	16.08
	$Q$ (kg)	0	4.0	0	8.2	0	12.0	0	0	15.28
	$f$ (cm)	0	0.5	0.5	1.4	1.4	3.1	2.4	1.9	Failure
Loading test 2	$g$ (kg)	4.6*	4.6	4.6	4.6	4.6	4.6	4.6	4.6	*4,6 kg is the self weight of the model.
	$Q$ (kg)	0	5.1	8.2	12.3	16.4	17.22	18.04	18.86	
	$f$ (cm)	0	0	0.8	1.3	2.4	2.5	3.2	Failure	

Evaluation of residual deflection after unloading

We note that:

- As designed, the 1:1 footbridge should support only 1 person's weight of  $5 \cdot 18,8 = 94$  kg
- The typology of failure is the **M4** mode of overall arch buckling, the only one that we could not precisely forecast by calculation.
- The hypothesis of classical arch failure mode is challenged by the fact that wicker is capable of resisting to tension, unlike a masonry arch. In this context, the experience shows that the ballasting of the footbridge is not an asset.

In order to increase the load capacity of the structure, we decided to add anti-buckling elements (bamboo tubes) between the deck and the ropes, the latter being self-tensioned with spacers in order to limit their deformation (it is important that the support of the tubes are completely blocked).

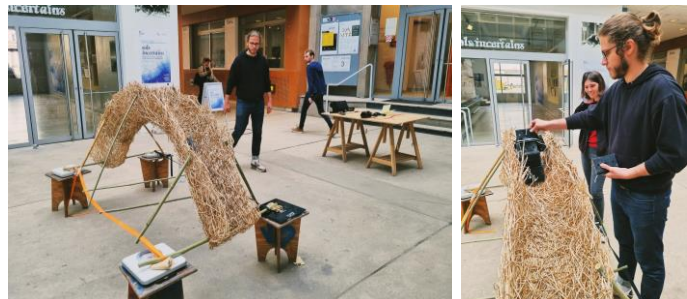


Figure 17: Braiding and loading tests on the 1:5 model.

Table 5: Results of load tests on the modified model (with anti-buckling).

Loading test 3	$g$ (kg)	4.6	4.6	8.6	8.6	12.6	12.6	16.6	16.6	20.6	20.6		
	$Q$ (kg)	0	4.0	0	8.7	0	12.2	0	16.8	0	20.7		
	$f$ (cm)	0	0.5	0.6	1.9	2.0	4.0	3.2	5.3	4.3	6.9		
Loading test 4	$g$ (kg)	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6
	$Q$ (kg)	0	4	8	12	16	20	24	28	32	36	40	44
	$f$ (cm)	0	0.5	0.9	1.5	2.0	2.8	3.6	5.0	5.8	6.7	8.0	Failure

We note that:

- Once modified, the footbridge should be able to support the weight of 2 to 3 people ( $5 \cdot 44 = 220$  kg). The main difference with the numerical prediction (400 kg) is that, in the numerical prediction, the load was divided into 4 loads of 100 kg each positioned at  $1/8$ ,  $3/8$ ,  $5/8$  and  $7/8$  of the length of the footbridge. Therefore, the physical model confirms, rather correctly, the BAYA numerical model.
- The failure occurred on the extrados at a stitch between module 1 and module 2 (we have 6 modules in total). The buckling started in the center of the footbridge: increased attention must be paid to the execution of the stitch, the handrails and to the tension of the ropes supporting the feet of the anti-buckling elements. Correctly doing that should increase significantly this result.
- The failure mode is **M1**. The local traction is maximum close to the base of the arch as it is expected in a classic masonry arch, because the position naturally taken by the funicular in an arch is that of passive thrust (the funicular is close to the intrados close to the feet of the arch, and on the extrados at its center). A rounded, braiding wicker handrail will be added to scale 1:1, to take up this traction on the extrados more efficiently.

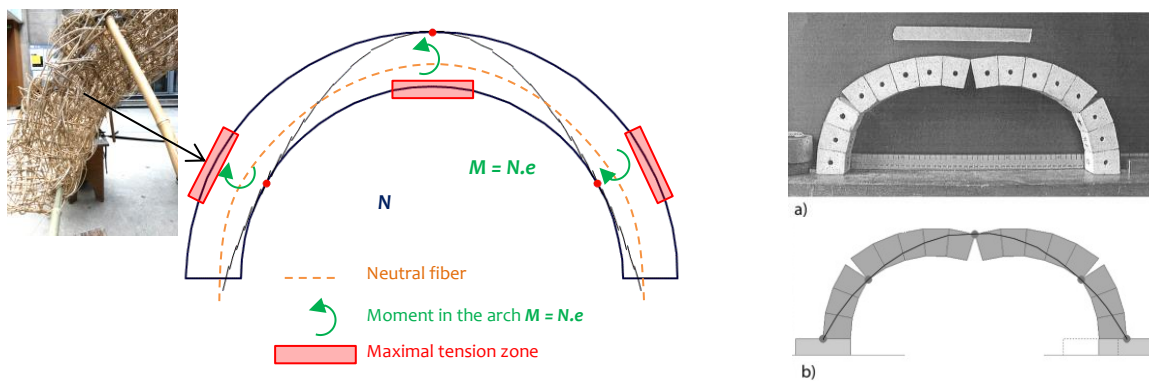


Figure 18: Failure of the wicker bridge and analysis of the zones of maximum traction, and analogy with the classical failure of a masonry arch (illustration from Galassi et al.[3]).

#### 4.4. Construction to scale 1



Figure 19: Construction of the footbridge during workcamp I (june-22). The bridge will be finished in august-22.

## 5. Conclusion

- Our footbridge uses 500kg of material and is made of 90,1% wicker (around 1 m<sup>3</sup>) plus 8.5% bamboo and 1.4% rope. In order to make a 100% footbridge, we should explore a tubular shape, more rigid, and therefore more stable regarding buckling. We could also avoid the ropes if the abutments could withstand a horizontal reaction.
- The data will be analyzed in order to develop a new version of BAYA. The objective is to integrate a first approach to the calculation of the deflection and to take into account the slip of the braided nodes. Another necessary improvement would be to evaluate global buckling failure loads numerically. After that, the contributions of the study of the wicker crossing will be transposable to other structural shell projects for architectural use.

## Acknowledgements

Benjamin Marolleau, from La Teinturerie, Christophe Kerrero, rector at Chancellerie des Universités de Paris, Florianne Le Thiez-Carotenuto from Chancellerie des Universités de Paris, Superior school of applied arts Boule, Superior school of applied arts Duperré, Campus métiers d'art, Séverine & Patrick Boyer (Osier de Gué-droit). Anna Danielsson. Geoffrey Clamour and Camille Sineau (BETA).

All the students, tutors and wickerworkers who took part in the workcamp.

Valéry Schollaert, ornithologist, Roger Hérisset, basketry expert and doctor in ethnology at the UBO, and Prof. Ph.D. François Guéna, Scientific Director of the MAP-MAACC laboratory (ENSAPLV). Pierre Jehel and Arnaud Lafont from the CentraleSupélec school. Joshua Guiffrey for proofreading.

The ENSA of Paris-la-Villette, Caroline Lecourtois, director, Vincentella De Comarmond, deputy director, Frédéric Sallet general secretary, Anne d'Orazio, President of the Board, Jérôme Candevan, accounting officer, Anaïs Campanaud, jurist, Philippe Agricole (maintenance shop), Philippe Bourdier, in charge of student life and Marc Fayolle De Mans, Jacques Bergna and Alain Raynaud (model workshop). Yann Nussaume, Rosa de Marco and Olivier Jeudy from AMP research unit. Suzel Balez, Nazila Belkadi and Dalil Hamani from the teaching team.

Salomé Chantob, Victor Bardy, Mélanie Bento students at ENSAPLV, Ethan Azerad, Emmanuel Berrebi, Théodore Tarride, Maggy Zhou, students at Central-Supélec. The students who participated to elaborate the BAYA algorithm and the Baya project in 2021. And those who has worked to improve the algorithm: Alexis Meyer, Bastien Frobert, Marc Pouyanne, Louise Delhaye, Jérôme Garcia.

## References

- [1] Bouhaya L., *Ph.D. Thesis – Optimisation structurelle des gridshells*. École doctorale science ingénierie et environnement, 2010.
- [2] Douthe C., *Ph.D. Thesis – Étude des structures élancées précontraintes en matériaux composites : application à la conception des gridshells*. ENPC, 2007.
- [3] Galassi S., Misseri G., Rovero L., Tempesta G., Failure modes prediction of masonry voussoir arches on moving supports, *Engineering Structures*, Volume 173, 15 Oct 2018, Pages 706-717
- [4] Leyral M., Chef Q., Guerold P. and Ebode S., 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.
- [5] Méry, É. Mémoire sur l'équilibre des voûtes en berceau. *Annales des ponts et chaussées*. Mémoires et documents relatifs à l'art des constructions et au service de l'ingénieur. Carilian-Goeury, Paris, 1840.