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.)

Les petits constructeurs: archs, vaults and domes explained to children.

Sylvain EBODE[*] and Marc LEYRAL*, Ludovic REGNAULT[b], Quentin CHEF[b]

[*,a] AMP Research Unit, ENSA Paris-La Villette, Paris
sylvain.ebode@paris-lavillette.archi.fr
[b] *Construire l'Architecture* research team

Abstract

According to an old saying, if one truly wants to understand a concept, one must be able to explain it to a 6-year-old child. To bring further proof to this adage, we challenged architecture Master students to explain complex concepts of structural morphology and spatial structures to young children from 6 to 10 years old. To this end, we organize each year a discovery day: "*Les Petits Constructeurs*" ("The Little Builders"), that benefits to both children and students. The theme of the 2024 edition is how funicular arches, vaults, and domes are working.

Our goals:

- Bring children from all backgrounds to enter the doors of a higher education establishment, foster awakening, interest, and even vocation.
- Hand down scientific knowledge using an entertaining approach, with quality materials and media.
- Break the verticality of teaching, promote exchange and mutual and intergenerational learning.

To meet these goals, the schedule of the day is:

- An entertaining conference with our guest, the artist Vincent Ganivet.
- 5 incredible experiences: giant igloo (20 m² puzzled dome to be built by the children), antifunicular system with helium inflated balloons, removing correctly the supports of an arch, VR stand simulating a jump on the moon, Heinz Isler frozen shells reproduced with liquid nitrogen.
- A guided tour of the historic domes collection of the Cité de l'Architecture et du Patrimoine.
- A Funicular arch game kit made by our team and distributed to every child.

Keywords: pedagogy, arches, vaults, domes, childhood, virtual reality, structural games.

1. Introduction

Every year since 2022, Master's students from ENSAPLV, along with the Construire l'Architecture and AAIIA associations, have organized an educational day for children aged 7 to 10 focused on the themes of architecture and construction, featuring participation from the CAUE of Paris

2. Origin

The origin of this teaching approach is based on a simple observation: students understand the knowledge they are supposed to acquire better when they have to reformulate it for an audience of non-specialists.

Sylvain Ebode and Marc Leyral, lecturers at the school of architecture of Paris-La Villette, conducted a similar experiment with undergraduate students, asking them to create educational tools (models, films, etc.) on assigned topics related to the discipline (moments of force, bracing, funicular arches, etc.), as part of their directed studies in the structural course. The challenge was to explain the principles to their classmates during an end-of-year presentation.

We found numerous benefits. Firstly, because the explanations were made in language that was perhaps more accessible or natural, the comprehension of the studied phenomena by the authors of the studies was better, as was that of the audience listening to them. We also discovered that our own understanding of subjects that we have been teaching for many years was deepened. Indeed, the seemingly naive questions from the audience sometimes turned out to be precious sources for a better understanding of the principles of transmission and could also lead us to re-examine certain disciplinary pseudo-evidence.

Thus, a discussion on the commonly accepted funicular/anti-funicular symmetry pushed us to clarify more clearly that we were operating within the framework of inextensible chains for reasons of simplifying calculations. But indeed, the two forms could not be rigorously symmetrical due to the elongation for one and the shortening for the other.

3. Objectives

The objectives of this pedagogical project are manifold. For Master’s students, it's about gaining a better understanding of a specific theme in construction and architecture: it is indeed necessary to have a deep comprehension of a subject in order to convey its profound meaning.

For the target audience, the question arose from the start. We wanted them to be naive, curious, and uninhibited so as to push our students to truly master their subject and to anticipate the most unexpected questions. We also aimed to contribute to the dissemination of architecture and construction to a young audience, so that these concepts are introduced early and perhaps better understood by the future adults they will become. Finally, we sought to modestly perform a social deed by opening our doors to the inhabitants of a so-called popular district. We thus achieved the following triple ambition:

- Allow young children from the first school cycle, between 6 and 10 years old, from all social backgrounds to step through the doors of a higher education establishment. This simple act creates a context favorable to awakening and interest, or even vocation.
- Perform an act of popularization by disseminating sometimes complex knowledge, using entertaining means, with quality supports and media.
- Place the students at the heart of the pedagogical question so that the transmission of knowledge is co-constructed between teachers, students, and a naive third-party audience. We see several virtues in this break from the traditional verticality of transmission: improving students' involvement and concentration, fostering exchange as well as mutual and intergenerational learning. This is, therefore, a pedagogy at the crossroads of several paths, addressing not only Master’s students at an architectural school but also young children, as well as the accompanying parents of the children and the teachers, including those at the origin of the project.

4. Educational walk

Following 14 weeks of 3-hour classes, we organize a walk within and outside the school. This walk is marked by themed educational stages, each allowing exploration of one facet of the year's topic.

4.1. Walking on the moon: understanding the concepts of gravity, mass, weight

With students: Antoine Pessiot and Ibtihel Bahri (state of the art and educational device)

The aim is to make the concept of gravity felt, then formalized and understood, and by extension, the concepts of mass, weight, and by generalization, force. This is the first step of the educational walk, the entry concept that establishes the fundamental notions children need to share a common vocabulary with the students and to better conceptualize the following stages.

4.1.1. Analysis for the Master’s class

The experiment proposes simulating a jump on a planet with weaker gravity than Earth's. For Master’s students, the initial goal is to understand a vertical jump in Earth's gravity, then extrapolate these results to a different gravity. This offers a chance to review some elementary concepts under the assumption that it will improve their understanding of the current model of gravity and forces as applied to the world of structures. We seek to determine what speed is necessary at the end of the push phase to make a 10 cm jump on Earth, and what this jump would be on the moon. The movement of a person during a vertical jump on the spot is divided into two parts: the push phase and the free fall phase. Taking as a basis the average characteristics of a 10-year-old child (Height: 127 cm, mass: 25 kg, leg length: 60 cm – divided on a first approach between 30 cm for the femur, and 30 cm for the tibia –), optimal take-off (difference between legs bent at 90° and legs straightened, $h = 60 - 30\sqrt{2} = 17.6$ cm), average duration of the push phase: $\Delta t = 1/4$ s.

What speed must be reached at the end of the push phase to make a 10 cm jump?

$$v_f = \sqrt[2]{{v_i}^2 + 2hg_t} = \mathbf{1.4\ m/s} \tag{1}$$

What acceleration is needed during the push phase to reach this speed? $a \approx \frac{\Delta \mathrm{v}}{\Delta \mathrm{t}} = \mathbf{5.6\ m/s^2}$ (2)

We considered that on the moon the speed at the end of the push would be the same (which is not strictly accurate because with identical muscular force, the acceleration will be greater on the moon).

Revisiting: $${v_f}^2 = {v_i}^2 + 2hg_l \tag{3}$$

The jump height on the moon would be h = **0.61 m**

Conclusion: at the same ejection speed, but with a lesser force, the jump on the moon will be six times higher than on Earth. Our task will be to construct a device that allows this to be felt and explained to the children.

4.1.2. Adapting to a young audience

The gravity reduction device is based on a double pulley and counterweight scheme.

Figure 1: Diagram and photos of the Low Gravity Device [S. Ebode, Q. Chef]

During the experiment, children are weighed, and students adjust the counterweight values based on the initial weight. The calculation is made based on lunar gravity, but the diagram shows that as the child rises, the compensation, which depends on the angle α, decreases. Thus, there is a natural braking that limits the jump's reach.

The vertical compensation force *Fc* must be equal to 5/6th of the child's weight *P* to simulate lunar gravity.

If h is the vertical distance between the pulley and the harness, l is the horizontal distance, and α is the angle the cable makes with the vertical, we have $\tan(\alpha) = l/h$, and the value of the traction in the cables, the value of the counterweights, is $T = \frac{5P}{12 * \cos(\alpha)}$

Students thus have a simple rule that allows them, based on the weight of the child, to associate counterweights enabling a jump on the moon as realistic as possible.

To perfect the illusion and anchor the experience in memory, a scene is set:

- Children put on an astronaut suit, then the suspension harness.
- Students have them wear a virtual reality headset containing a custom program simulating the view from the moon's surface. We even integrated Tintin's rocket, and this reference did not particularly resonate with them, much to our dismay.

Figure 2: Low Gravity Device and Virtual Reality [photo: Q. Chef]

4.2. Chocodome: Following in the Footsteps of Heinz Isler, Nature as a Guide

With students: Amandine Langella and Dilara Kaysal (state of the art) and Arthur Cariot and Romuald Tournade (pedagogical device).

4.2.1. Analysis for the Master's class

Understanding the workings of domes necessarily involves the ability to visualize the forces constraining the material, tension, and compression, and recognizing that only compression is permissible for arches and vaults. To realize this, examples of dry masonry, like the Armadillo Vault by the Block Research Group at the Venice Biennale of 2016, are particularly illustrative since it's clear that tension would cause the stones of these equilibriums to come apart.

Figure 3: Armadillo Vault, Block Research Group, biennale de Venise, 2016 [Anna Maragkoudaki]

Following this realization, we are led to question the form finding: is there a form that ensures the masonry elements of a vault are well compressed and, if so, how to find it? A centuries-old question as shown by Bélidor's statement in 1725: “Problem: Find the curve that should be given to a vault, so that all the voussoirs, being equal in weight, are in equilibrium?” [1]

This leads to the search for the antifunicular form, or curve of pressures, by inverting the funicular form of tension – a principle often illustrated by the shape of a chain hanging under its own weight: Ut pendit continuum flexile, sic stabit contiguum rigidum inversum, meaning “As hangs a flexible line, rises a rigid arch, but inverted.” [2]

4.2.2. Adapting to a young audience

Here are complex principles to grasp for children aged 6 to 10: we must resort to examples. The chains and weighted sheets of Antoni Gaudí immediately come to mind – we will revisit this for the following pedagogical device – but as an introduction, we opted for an even more playful approach inspired by the form-finding research of Heinz Isler, an engineer from ETH Zurich in the second half of the 20th century, who used night freezing to solidify the funiculars of his projects, designed from damp sheets, in order to invert them to lift the form. This served as a basis for constructing large thin-shell concrete domes.

Figure 4: Heinz Isler's Frozen Sheets, Félix Candela's Los Manantiales Restaurant in Mexico (1958), and Heinz Isler's Sicli Pavilion in Geneva (1969) [[3], MHM55]

The stiffening of the suspended flexible shell is necessary. Without it, the inverted and thus compressed form would buckle under its own weight. The main challenge for our team was to achieve this in both a captivating way, to hold the children's attention, and quickly since each experience has half an hour. We opted for cooling with liquid nitrogen, a gas that vaporizes at -196°C and thus serves as a surprising substitute for the more traditional use of plaster. After inversion, we attempted to give the children an initial idea of the concept of formwork by brushing and forming an edible dome with melted chocolate over the frozen fabric.

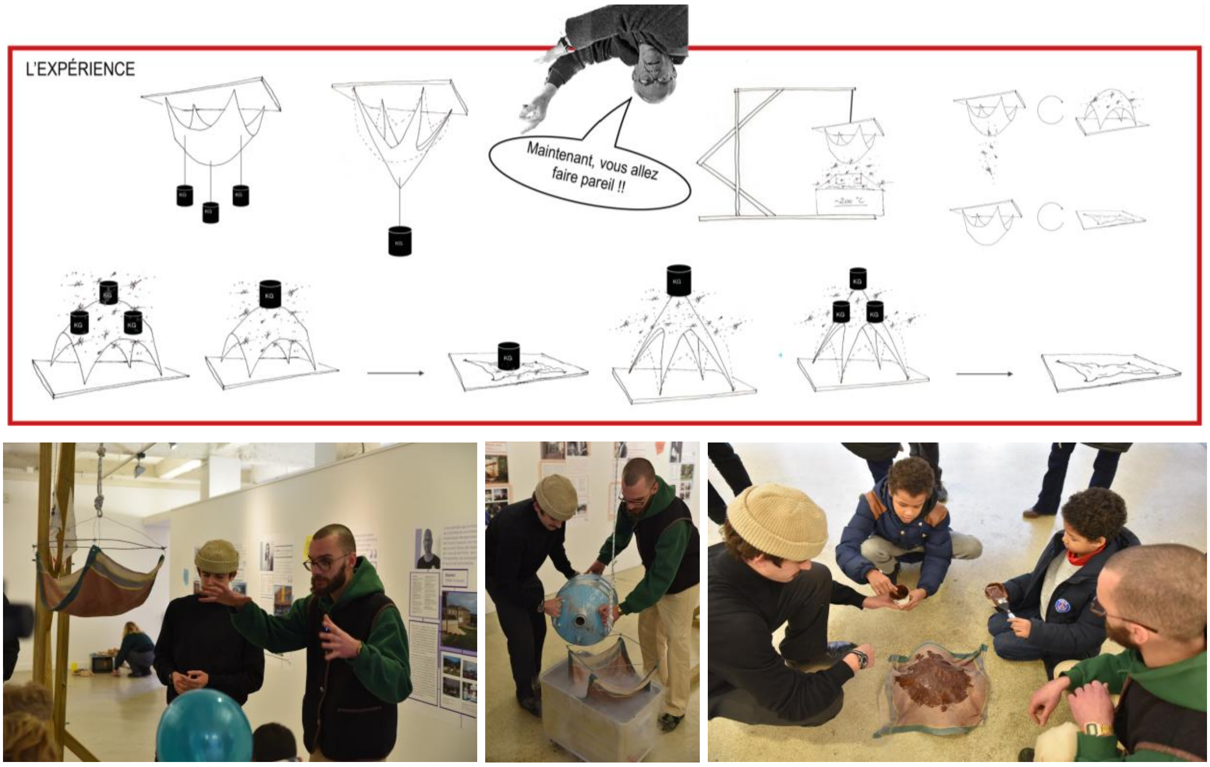


Figure 5: Explaining the search for anti-funicular shapes to children [Les Petits Constructeurs 2, photos Q. Chef]

4.3. The Balloon Dome: Lighter Than Air

With students: Olivia Blanjin (state of the art) and Rachanon Kamoljitravee (pedagogical device).

4.3.1. Analysis for the Master's class

Sensing that the concept of the funicular, as subtle as it is fundamental, required a second perspective for effective transmission to children, we decided to set aside the issue of the necessary rigidification of the shape and explore the tricks that allowed for inverting the funicular without resorting to it. The most well-known among these are those employed by the Catalan architect Antoni Gaudí – famous for designing the Sagrada Família in Barcelona – who, to find the natural and ideal forms of his projects, made suspended models out of chains or weighted sheets, before observing them in a mirror on the floor or ceiling to discover their inverted shape.

Figure 6: The funicular explained to children, with the examples of a suspended chain model from Casa Milà [Alexandre Borovik], a scale model of the crypt from Park Güell compared to the Sagrada Família of Antoni Gaudi (1852-1926), and the floating dome by P. Block at Bois Buchet [Zito Tseng CIRECA].

4.3.2. Adapting to a young audience

From suspended chain models, we derived a discontinuous approach to the shell, as opposed to Heinz Isler's frozen sheets that formed a continuous surface. On this basis, and to maintain a captivating effect useful for capturing the children's attention, we drew inspiration from a floating balloon dome by the Block Research Group at Bois Buchet to allow children to observe the inverted funicular while remaining in a tense form. This feat is enabled by the density of helium, which, being lighter than air, allows for creating "masses" that operate in "antigravity," meaning the forces act vertically but upwards.

Figure 7: The funicular and its sensitivity to the position of loads [Les Petits Constructeurs 2].

The advantage of this stand was that children could easily observe an essential aspect of domes: the variations of the funicular shape depending on the position of variable loads. To do so, they could freely add or move the balloons around.

Finally, we expanded this idea to some "classic" cases of two-dimensional arches: Roman arches, Gothic arches, parabolic arches, and catenaries, so that children could understand that all these forms are funiculars and that if these varieties of forms exist, it's because the funicular depends on the load case and, therefore, on the overall design and construction method of the project.

4.4. Striking the Arch

With students: Olivia Blanjin (state of the art), Lena Gilardino and Caro Esprit (pedagogical device).

4.4.1. Analysis for the Master's class

When the necessity of the funicular shape under a given load case - generally the self-weight of the structure - is well understood, and when we are well informed of the funicular's sensitivity to load variations, we often question, even fear: what happens if the funicular, under an unexpected, concentrated, and significant variable load, were to move out of the arch? As demonstrated by Navier [4], if the funicular moves out of the central third of the arch, the section of the arch is no longer entirely compressed: a hinge may form in the arch, and if two are formed within it (in addition to those naturally existing at both feet), it will no longer be stable. If the funicular moves out of the arch, the section at the anomaly will be entirely decompressed, and the arch will collapse.

Thus, the stability of the arch is extremely sensitive to load variations. In the first half of the 19th century, Édouard Méry, a civil engineer, summarized the problem as follows: "When a heavy burden is passed over a vault, the pressure curve successively takes various shapes, as would a suspension chain and, while it undergoes these oscillations, it must always remain enclosed between the intrados and the extrados of the vault for it not to fall." [5]

When thinking of a variable load, the idea of a roadway bridge with traffic halted mid-crossing might come to mind. We naturally think of the effect of operational loads or climatic loads such as those related to wind. In the pedagogical device for striking the arch, we wanted to highlight a variation of load related to the execution of the arch. More unexpectedly for the audience, this example simultaneously brings up the constructive mode useful for erecting the arch.

Indeed, the way the centering - the wooden scaffold that temporarily supports the arch under construction - is removed once the work is completed affects the loading of the arch and, therefore, the position of the funicular inside. The subject can be summarized as follows: "If you remove [your formwork in pieces], you load only a part of the arch while the rest is still supported by the props. The loading no longer corresponds to the uniformly distributed load across the entire arch that you used as the basis of your design. The corresponding funicular will then move out of the thickness of your arch; tensions will appear, the arch will decompress locally and collapse. (…) In the past, formworks were placed on a sand box: a container holding very dry sand on which a plate that supported the centering was placed. Once the arch was completed, outlets regularly spaced in the box were opened. The sand's evacuation caused the plate and therefore the centering to descend. For large structures, there could be several sand boxes. It was then necessary to coordinate the workers so that their drainage occurred simultaneously." [6]

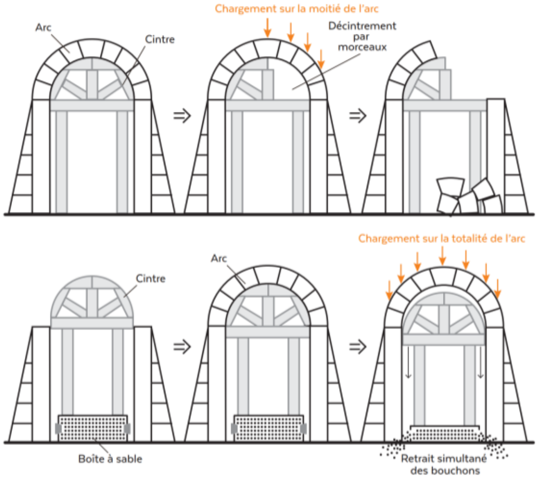
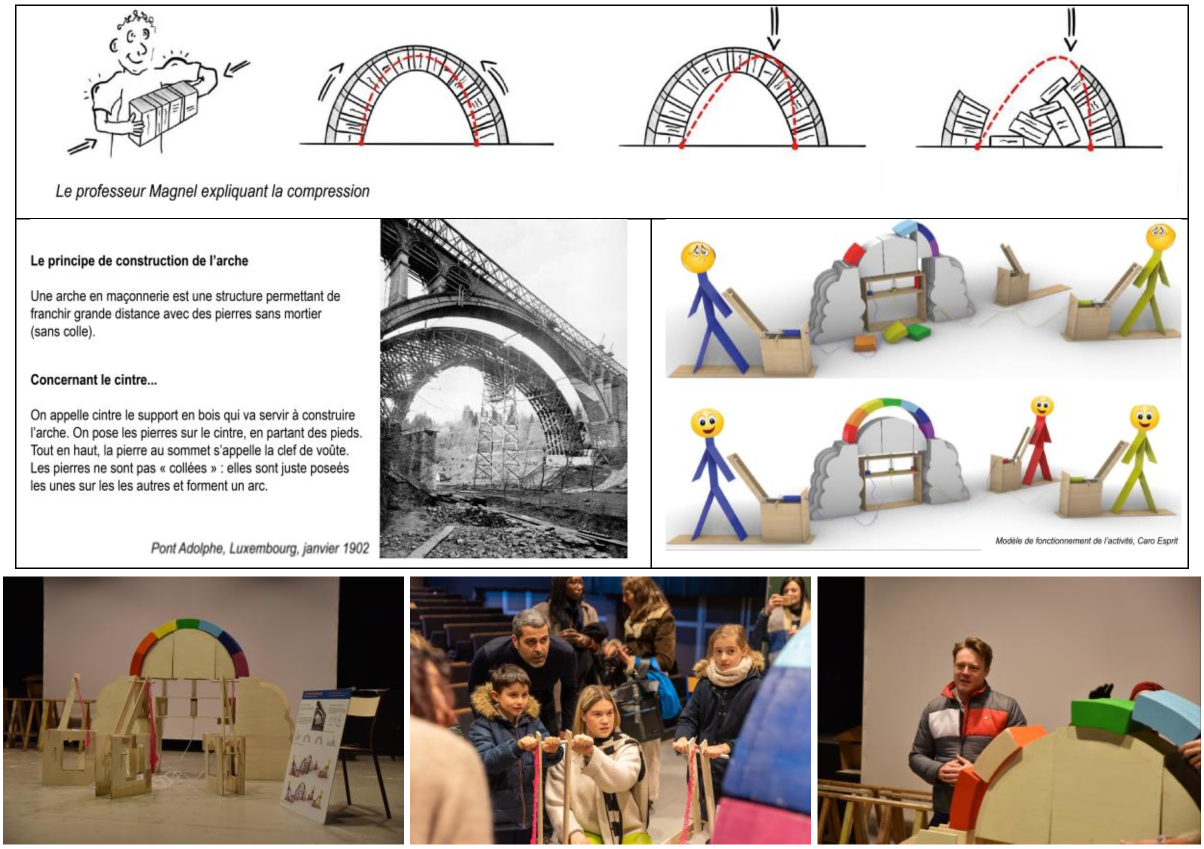


Figure 8: The principle of striking and loading of arches [M. Leyral [6]]

4.4.2. Adapting to a young audience

To convey these concepts to children, the focus was on coordinating the young team playing the role of workers on the site. The arc bending device was formed of three asymmetrical pieces. Each piece of centering was independently connected to a jack that could push it up or down. Each jack was linked to a lever accessible to the children. Without instructions, the children operated the levers, thus lowering the centering pieces randomly, causing the inevitable collapse of the arch as previously explained. Only an awareness of the phenomenon and the necessary coordination, aided by the explanation from the monitors, allowed the children to operate all three levers simultaneously to strike the arch in one go, loading it uniformly and preventing its collapse.



Le professeur Magnel expliquant la compression

Le principe de construction de l'arche

Une arche en maçonnerie est une structure permettant de franchir grande distance avec des pierres sans mortier (sans colle).

Concernant le cintre...

On appelle cintre le support en bois qui va servir à construire l'arche. On pose les pierres sur le cintre, en partant des pieds. Tout en haut, la pierre au sommet s'appelle la clef de voûte. Les pierres ne sont pas « collées » : elles sont juste poseés les unes sur les les autres et forment un arc.

Pont Adolphe, Luxembourg, janvier 1902

Modèle de fonctionnement de l'activité, Caro Esprit

Figure 9: Striking of an arch explained to children [Les Petits Constructeurs 2, photos Q. Chef].

4.5. The Igloo: A Collaborative 3D Puzzle.

With students: Haroune El Hidaoui and Adam Flissate (state of the art and pedagogical device).

4.5.1. Analysis for the Master's class

Driven by students' craving for digital, we decided to erect a three-dimensional puzzle in the form of an igloo, originating from a parametric design known as the "digital continuum," a concept developed within the school by the MAP-MAACC laboratory led by François Guéna.

The challenge for the students was to apply their understanding of funicular surfaces to the design of a simple funicular shell, and to automatically extract thick planar facets, achievable in polystyrene sheets (with Rhino3D and Grasshopper). Lacking a hot-wire digital cutter, it was necessary to extract the lower and upper planar faces of each module from the model, cut them with a digital cutter, and then glue them onto the polystyrene pieces, taking care to respect the relative positions of the edges in space: a substantial effort greatly underestimated by the students in charge of the igloo.

Figure 10: Grasshopper Definition and Resulting Rhinoceros Model [Les Petits Constructeurs 2, Sylvain Ebode].

4.5.2. Adapting to a young audience

In this workshop, which proved too complex, children, aided by their parents, had to form a living and collaborative formwork for setting up the igloo, which lasted only a few seconds but was nonetheless a learning source for our students: despite efficient digital tools, bridging to reality can prove complex, the model is not reality.

And for our young audience, a source of amusement was watching adults labor in vain to erect a construction. They experienced the same difficulties, as the workshop also offered them to test the assembly of playful catenaries made for their attention (see §1.3).

Figure 11: Human Formwork Workshop Chain Test [Les Petits Constructeurs 2, photos Quentin Chef].

4.6. The Gift: Art and Structure

Each edition is graced by the presence of a guest whose reflections relate to the proposed topic. For the 2023 edition, we invited the artist Vincent Ganivet to present his work, marked by a fascination for balances and particularly anti-funicular forms.

He has produced numerous works that celebrate humble materials such as concrete blocks, which he elevates through bold implementations that surprise the mind.

During a conference aimed at all, but especially at children, he was able to explain his journey, showcase his works, and reveal the close links between art and science, aptly in an architecture school setting.

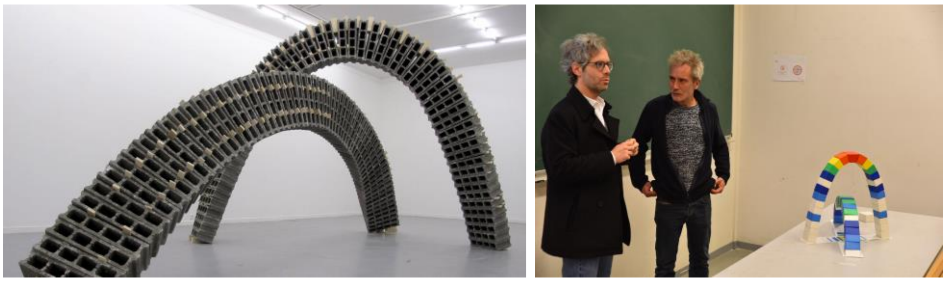


Figure 12: Catenary arches in cement blocks and painted wooden toy [Vincent Ganivet].

Vincent Ganivet also designed a toy, inspired by one of his monumental works, made of containers forming two catenaries. The principle is simple: each color defines a specific voussoir with its specific angles, with all the pieces allowing the construction of the two catenaries, or the exploration of other assemblies. He graciously agreed to temporarily cede the rights to his toy, and we were thus able to manufacture a copy for each child, providing our students with the opportunity to practice 3D printing for the positives, and silicone molds for mass production.

Figure 13: Jesmonite-tinted Chain Workshop [Quentin Chef].

Beyond its playful function, this toy serves as a mnemonic anchor; it eternally imprints in the children's memories the words catenary, funicular, and arch, associating them with accurate and joyful images.

4.7. The Visit to the City of Architecture, the Institutional Framework

To conclude this day, the afternoon is spent at the City of Architecture and Heritage (https://www.citedelarchitecture.fr/fr), a partner of the event where speakers await us. They will tell us how builders, over time, have embraced these concepts to create architectural works.

Figure 14: Guided Tour of the Cité de l'Architecture et du Patrimoine [Quentin Chef].

5. Conclusion

This method of knowledge transmission finds some of its origins in the Christmas lectures initiated in 1825 by Michael Faraday at the Royal Institute in London. From that time to the present day, an annual lecture has been organized each Christmas to popularize scientific knowledge to a broad audience, partially comprised of children. Our project shares this intent to inform while entertaining.

It also incorporates some principles of what is known as action-based pedagogy, which we try to adapt to the specific context of applied sciences: students, both young and old, must collectively conduct concrete actions that allow them to experiment before understanding. This collaborative aspect is crucial as it enables learners to co-construct knowledge through communication, the senses, and creativity.

These observations effectively place us within a specific field of pedagogical research known as action research, which we plan to explore further. This will involve the implementation of evaluation tools to objectively measure its effectiveness. We eagerly anticipate that edition 03 will take us further into understanding this phenomenological dimension of knowledge acquisition.

References

[1] Bernard Forest Bélidor, *De la mécanique des voûtes*, 1725.

[2] Robert Hooke, *A Description of Helioscopes, and Some Other Instruments*, 1676.

[3] John Chilton, Heinz Isler (*The Engineer's Contribution to Contemporary Architecture*, Inst of Civil Engineers Pub, January 1, 2000.

[4] Henri Navier, *Résumé des leçons données à l'École des Ponts et Chaussées, sur l'application de la mécanique*, 1839

[5] Édouard Méry, 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.

[6] Marc Leyral, *Faire Tenir – Structure et architecture*, Éditions de la Villette, coll. Savoir faire de l'architecture, Paris, 2021.

Acknowledgements

All the children, parents, and organizers. Association AAIIA: A. Paporello, O. Guillouet-Lamy, G. Bernard Guelle, I. Lalanne, T. Barna, L. Delebarre, association Construire l'Architecture: L. Genuys, M. Hymans, C. Lanièce ; CAUE de Paris: S. MOUREY ; ENSA de Paris-La-Villette : Jacques BERGNA, Marc Fayolle de Mans et Alain Raynaud (Model workshop), C. Baez, C. Lecourtois, V. De Comarmond, N. Amzil, S. Bruna, A. Guesdon, reception and storage agents. Cité de l'architecture et du patrimoine : F. Servole, P.-O. Cedille, D. Blouet et A. Cottais. Sponsors: AIA Life Designers C, Würth France (S. Conord), la MAF. Videographerses M. Gholam from Le Nouveau Programme (LNP) and V. Haasser.