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Straw, from modelling to full scale

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Abstract

In the two weeks 'Intelligent Fabrication 2023' Workshop, led by Ass. Prof. Klaas de Rycke and Ass. Prof. Dr. Gilles Retsin, students explored 1:1 scale straw construction through an architectural design process blending advanced technologies with the use of low-tech materials. Initially, abstract lines and conceptual sketches were merged using artificial intelligence, then refined by hand to create preliminary plans for the final construction. Through various iterations, students learned to use artificial intelligence as a genuine tool for design, bridging the gap between traditional sketching and computer-assisted design, rethinking the process of discretization. The resulting outcomes provided a basis for exploring the constructional and structural characteristics of straw: students developed their projects by manipulating small-scale models and 1:1 straw bales, tying to optimize the structure with digital tools as Karamba. The example of the straw-supported beam illustrated how materials complement each other, underscoring the need to decompose forces while minimizing the use of additional materials (cables and wood) to ensure stability and durability. By combining student creativity, traditional practice, artificial intelligence, and structural optimization, the results demonstrated the synergy between advanced technologies and low-tech materials. This method ensures each material and tool are used at the right moment and in the right measure—an approach essential nowadays.

Keywords: Straw, Artificial Intelligence, Karamba, Structural optimisation, Discretized architecture

1. Introduction

Advancements in construction and design methods have influenced the way architecture is approached, leading to the design of increasingly complex structures. With the introduction of new digital tools, we have been able to push the boundaries of what is possible, enabling the creation of forms and structures that were previously unimaginable. These digital tools have added an extra dimension to design, necessitating the establishment of new workflows.

The emergence of artificial intelligence and digital tools raises fundamental questions about the role of the computer in the design process. How does the interaction between humans and machines influence the creativity and decision-making process of architects and engineers? How can we ensure that these digital tools serve as true catalysts for innovation rather than simple task facilitators? These questions underscore the need for critical and ongoing reflection on the impact of technology on architectural practice.

Furthermore, the integration of bio-sourced materials, such as straw, remains a major challenge for digital processes. These materials offer undeniable ecological benefits, but their use requires a deep understanding of their structural properties and adaptation of existing design tools. The framework is still missing: predictability, scientifical and physical knowledges. It is essential to do fundamental research on materials and their properties to overcome obstacles against using it in the built environment, based on previous experiences like prestressed stone. [1]

In this context, the "Intelligent Fabrication 2023" Workshop was conceived as an empirical approach to explore these issues. Under the direction of architect Dr. Gilles Retsin and Assoc. Prof. Klaas De Rycke, the workshop served as an experimental laboratory where students were invited to rethink architectural conventions using straw as the main material. The workshop emphasized the pedagogical integration of digital tools, structural analysis, and material constraints. By leveraging parametric digital tools and artificial intelligence, students learned to adopt advanced technologies while working with bio-sourced materials at full scale. This educational approach aimed to teach students how these diverse knowledge areas can influence one another, encouraging a holistic understanding of contemporary construction challenges.

2. Building with straw

2.1. Straw as a building brick

Straw construction already has a long history: the first straw houses were built in North America (Nebraska) out of haystacks, as timber or stone supplies were lacking. Straw bales were stacked on top of each other, working in compression, like a masonry wall. The walls were stabilized at their top by a timber roof. If the straw was initially structural, in many straw constructions that were observed later, straw became mainly as part of composit complex of facade, or even as an insulating filler within a timber structure.

With a very low stiffness and a high deformability, straw bales are indeed preferred for their insulation and acoustical properties. Hybrid constructions with a timber frame filled with straw combine the strength and stability of timber structures with the advantages of the straw. The Maison Feuillette in France, which has celebrated its 100th anniversary, well illustrates this principle and demonstrates its longevity: the straw bales have not aged a day.

If the straw material was neglected during the second part of the 20th century, the current debates on natural resources in the construction field reintroduces the topics. New experimentations are carried out by associations all around the world, and more especially in France, with associations like Nebraska, of the RFCP (Réseau Français de la Construction en Paille), developing knowledge and new construction solutions:

- Straw as insulation within timber frames
- External thermal insulation with straw for building refurbishment
- Bearing straw buildings
- Structural straw with concrete coating (GERB technic)

Since 2012, the association RFCP drew up the first professional rules and norms for straw construction, leading to a rapid emergence of numerous straw buildings. But when it comes to bearing straw, experimentations are still being carried out and the rules are still being defined. A strong state of the art already exists, with several built projects (Maison Libération in Grenoble, 2-storey houses in Switzerland, France, or in the USA…) while at the same time, explorations to discover the full potential of bearing straw bales.

This context provides an interesting environment for a workshop for students in architectural school: a bio-sourced material, available in large quantities and most of the time considered as a waste, easy to manipulate with potential to explore.

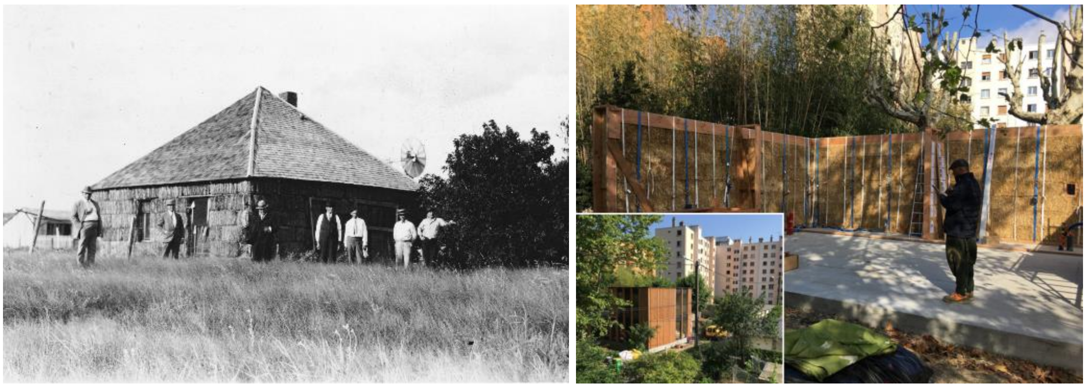

Fig. 1. Load-bearing straw house in Nebraska 1920’s on left and Load-bearing straw house by the association Nebraska in Grenoble on right, France, [2]

2.2. Straw properties

Straw bales are structural elements that works quite in compression, but that have no tensile and very low shear strength. The common bales used in straw construction are small bales of 37cmx47cmx(80to120)cm, that have a density around 120kg/m3.

Load-bearing straw structures are built according to the original Nebraska technique. Straw bales stacked in staggered rows, strapped of not, but always compressed between the bottom and top rails (prestress), to keep it under compression. Regular pins (wooden cleats, bamboo sticks, …) can regularly pass vertically through the rows to ensure alignment and stiffen slightly the wall. There is no real compression limit to the straw bales, the limiting factor being its settlement under heavy loads and the instability that can be induced by high settlements. Straw has indeed a very low Young Modulus that is estimated around 0.35MPa (representing 1/1000 of the elastic modulus for rammed earth as a first comparison). Prestress design of straw walls reduced also the settlement variation under live loads, interesting for such elastic materials. According to the state of the art and the construction methods that derived from it, straps are regularly tying up the wall on site (every 50cm approximatively), inducing a prestress. As long as the loads applied on top of the wall remain smaller than the prestress, the effect on the straw and the deformations will remain invisible. As common values, the state of the art recommend a prestress of approximatively 500kg/ml for a usual 47cm thick wall, and a maximal loading of 1000kg/ml in total under live load. These values correspond easily to the design of a ground floor or a 1-storey house. [2]

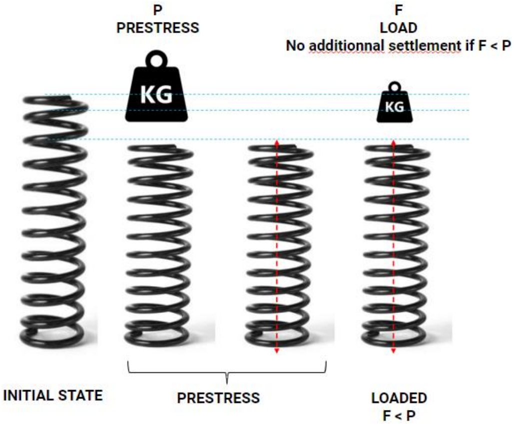

Fig. 2. Structural idea of prestress for straw used in the Workshop for other element: beams, columns etc. [2]

In addition to global and local settlement, straw construction is very sensitive to creeping effect: the settlement evolves with time, and can reach additional 2% during the first month, meaning that for a 3m high wall, the creeping effect can reach 6cm of additional settlement before settling permanently. The creep is actually translated into a loss of prestress and need therefore some surveillance on site. These values have not been standardised yet but are based on feedback from projects and French practical guidelines. [2], [3], [4], [5]

2.3. Experiential pedagogy

A low Young modulus material does not appear as the best compressive material for bearing structure as it asks to strongly and precisely evaluate the prestress, the settlements and the creeping effects. However, it is also a very good material for students to understand structure, stress paths, local stress concentration, tolerances and imperfection. Visible deformations make the interpretation of the mechanical behaviours easy.

First experiment to raise the students' awareness on this phenomenon was to measure the straw bales Young modulus, to understand its value and the orders of magnitude of the resulting deformations under loading.

With the properties of straw clarified and its use as a compression element being evident for the students, the question is: should we really limit ourselves to vertical walls? What systems can be imagined to overcome the weaknesses of straw and "capitalize" on its strengths? What freedom of form can be achieved?

Even if it is not optimal, the main objective is encouraging the students to test many structural elements or geometries, push back the limits of the straw, and understand every observed behaviour.

The structural and material exploration during the "Intelligent Fabrication" workshop in 2023 was a crucial step in enabling students to understand straw as a material, comprehend its properties, and envision the possibilities it offers as a construction material. Learning by making combined to digital modelling is a continuation of previous editions since 2016. The digital twin should enhance the power to project multiple solutions based on physical learning. Students embarked on a series of experiments aimed at assessing the structural viability of the material and exploring different techniques to enhance its load-bearing capacities.

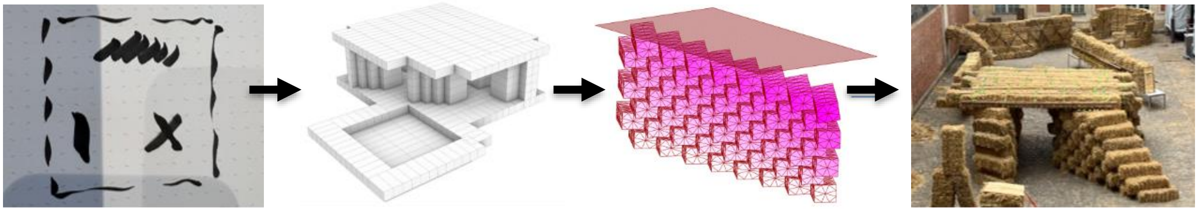

Fig. 3. Workflow: sketches+IA ‣ automated 3D ‣ calculation ‣ construction [6]

Starting from traditional straw construction techniques, such as pre-tensioning with straps and framing with high and low rails, tying bundles to improve resistance to shear forces, and exploring openings, students were able to identify the various challenges associated with the use of straw. They understood the material and its reactions under various constraints and put the learnt correlations in a set of design rules in a digital environment, in an attempt to push its limits by prototyping multiple solutions. Prior physical experiments on 1:10 scale models to understand the static patterns allowed them to verify the feasibility of their design concepts.

Fig. 4. 1:10 scale models: construction ‣ 3D ‣ IA ‣ sketches

3. Straw modelling

3.1. Understand the behaviour

As simple, low-tech, and historic as straw construction may be, its justification regarding resistance and stability remains empirical, and the calculation approach is simplistic and based on trials and tests, as demonstrated in the 'Intelligent Fabrication 2023' workshop. Traditionally, straw construction has not relied on advanced modelling techniques, but the goal was to push students to immerse themselves in digital tools. By doing, they learn how these tools can aid in their exploratory processes, enabling them to generate and create designs that might not have been possible otherwise. Using advanced modelling techniques allows students to receive feedback on their physical experiments, providing explanations for their observations and helping them anticipate potential issues. This iterative process turns digital tools into integral components of full-scale design exploration and testing. Consequently, integrating straw into a dynamic process of exploration and design of architectural forms presents a significant challenge. The complexities involved in the design and modelling of straw structures question the usual methods of structural analysis, prompting students to rethink and innovate in their approach.

First of all, the analysis of the structure stability must take into account the significant imperfections of straw bales and the very low Young's modulus of the material: relatively low forces can generate significant settlements and worsen the effects of imperfections to the point of instability. Even on elements with a simple shape (curved wall, or simple trussed beam) imperfections cannot be taken into account by formulas and must be integrated directly into the calculation model.

Secondly, the feasibility and durability of straw constructions depends on their prestressing by tensile elements (straps, bars, etc.). In the study of structural prototypes, one of the major challenges is to understand this phenomenon: what for the tension elements, what influence on the design, what orders of magnitude? Realistic modelling must therefore enable the use of non-adherent prestressing to be represented reliably.

Finally, straw structures are made up of modules (straw bales) joined together and transmitting compression forces and, to a lesser extent, shear forces. In that sense, their behaviour is similar to masonry. Usually, this type of structure is analysed as a continuous monolithic material with equivalent properties, assuming linear behaviour, then checking the linearity conditions. However, given the size and weight of straw bales, the limits of these assumptions are very quickly reached, especially for pure compression. More precise modelling by block and their interfaces is then necessary. This analysis is used to study certain types of masonry behaviour but is still very specific and not widely used. While there is considerable ongoing research in this area, it remains a complex and challenging pursuit, marked by significant technical obstacles and a lack of fully adapted methodologies. [7], [8], [9]

3.2. Model the behaviour

A model capturing these three phenomena (volume finite element modelling, integrating non-linear links between straw blocks, prestressing and imperfections) is far too complex for a clear and efficient design process especially for student use. The challenge of the process is to be able to tackle the problems of straw design, while integrating it into the workshop's dynamic design, exploration and prototyping process.

To address the educational goals of the workshop, three different tools were made available to the students to simplify modelling while studying the structural issues outlined above, depending on the sensitivity of each system. The primary aim is not to perform exact calculations. Instead, the goal is firstly, to demystify the complexity of 3D tools by having students manipulate intuitive elements, and secondly, to develop their structural intuition through digital tools. This process is primarily qualitative, giving students a sense of scale and proportion rather than precise measurements.

In this context, the workshop's educational aim is to train students in the use of structural modelling and analysis software within the Rhino3D environment and the Grasshopper plugin. These tools are particularly effective in discretizing shapes and surfaces into a series of modules. Additionally, several plugins are available for analysing the structure and its stability. While striving for accuracy, the emphasis is on practical, hands-on understanding rather than theoretical precision, fostering a deeper appreciation and intuitive grasp of structural concepts.

Firstly, to explore the stability of straw block stacking, we utilized the PhysicX module on Grasshopper, a graphical calculation module from video games which can model solid bodies under gravity and their intersection and allows friction coefficients and imperfections to be adapted. This module allows us to assess how sensitive straw structures are to variations in parameters such as curvature or wall orientation. It is particularly useful for experimenting with a huge amount of different structural configurations. While it provided insights into stability during assembly stages, its inability to simulate prestressing limits its application to straightforward shapes and temporary construction phases. Nonetheless, its simplicity and interactive nature make it an engaging entry point for students to grasp fundamental concepts in structural analysis even if it cannot provide valuable scientific results.

Two tools, Kangaroo and Karamba3D, can be used to analyse structures incorporating prestressing. As these two Grasshopper plugins cannot handle volume models, the straw bales are modelled as their six faces, with an equivalent thickness giving them identical stiffness properties.

Kangaroo was used for its realistic prestressing and solid contact features. This makes it possible to model the structures and check the actual deformations, joint openings and relative instabilities. On the other hand, the software does not allow real forces linked to the loads and weights of the structures to be extracted.

Finally, Karamba3D introduces additional complexity due to its capability to simulate prestressing effects, necessitating the modelling of linear contacts between straw bales to accurately represent tension and compression forces. This tool integrates parameters such as Young's modulus and deformation characteristics, providing insights into the structural behaviour beyond simple stability assessments. The primary objective here is not precise prediction but rather to derive approximate behavioural parameters such as stress distribution and deformation tendencies, that inform design decisions. This approach allows students to evaluate the relevance of their designs, ensuring optimal placement of structural elements like cables and assessing the magnitude of anticipated forces. It also aids in identifying potential issues such as excessive deformations, ensuring designs meet performance criteria and minimize risks during construction and service life.

The parallel use of these three tools, together with the use of 1:10 scale models and 1:1 scale tests, enabled to understand the behaviour of a complex material such as bricks, while experimenting with new geometric and structural configurations quickly and checking their feasibility and constructability before building.

3.3. Beyond physical limitations with artificial intelligence

Following the testing of digital tools, inspiring by the work of Achim Menges [10] about Morphogenetic, along with the analysis of their behaviour, to push the exploration, and free design from any preconceived ideas, artificial intelligence was added in the process and MidJourney was chosen.

Artificial intelligence is revolutionizing architectural design processes, enabling architects to explore new levels of creativity and efficiency. The Intelligent Fabrication 2023 workshop exemplified this fusion of human creativity and algorithmic power, allowing students to push the boundaries of technology and materials. A key question emerged: how can AI be effectively integrated into architectural design, particularly with traditional materials like straw? This workshop challenged conventional limits and preconceptions about straw, leveraging the unique capabilities of AI to broaden design opportunities. Asking an AI to "draw a line" differs significantly from the architect's act, which involves contextual understanding and technical intuition. By controlling the level of input data, we can liberate ourselves from constraints and unlock new possibilities.

Fig. 5. Images obtained by MidJourney to obtain a pavilion in straw

The workshop methodology involved an iterative and collaborative approach, where students freely explored integrating artificial intelligence and straw into their designs. They started with manual design, then submitted ideas to an AI platform, Midjourney, for new variations. Through iterations, they refined designs while preserving their creative vision. This hybrid approach allowed them to explore new design paths and push temporal constraints, all while building physical scaled prototypes to further understand module possibilities and straw integration. In this aim, inspiring by Ass. Prof. Dr.Gilles Retsin and his work about discretised architecture, a script was gradually developed to automate the transition from 2D to 3D modules. [6]

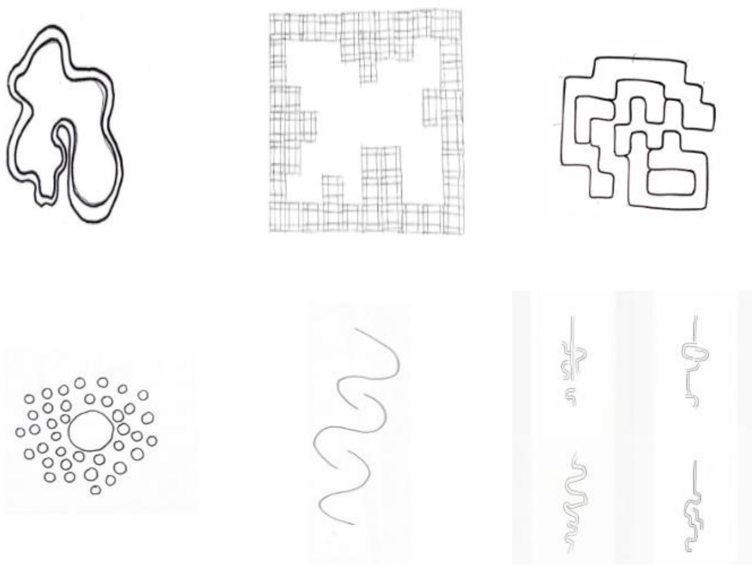

Fig. 6. Sketches generated by MidJourney after implementation of the students' drawings

In this process, AI and subsequent student iterations prompted a rethinking of traditional limits and barriers in architectural representation, focusing on essential sketch elements rather than societal norms. While this approach was interesting and offered valuable insights, the results could not be integrated into the final pavilion. The AI-generated designs provided a wealth of creative ideas and pushed the boundaries of what could be envisioned using straw and other traditional materials. However, several challenges emerged during the process. The AI's interpretations often lacked the necessary structural integrity and practical feasibility required for real-world construction. This highlighted a significant gap between conceptual design and practical application, especially when working with bio-sourced materials like straw.

4. From an experimental workshop to a straw pavilion at Archifolies 2024.

4.1. Geometric possibilities, form-finding and vertical elements

In the research process, to further the analysis and continue experimenting with straw, a comprehensive examination of all architectural elements was conducted. The primary traditional structural element in straw construction is the wall. Vertical, straight, or curved depending on the layout, as it is easy to bend straw bales and deform them to follow the curved imprint of a wall, the wall is intended to bear vertical loads. It is usually reinforced by other elements such as cross walls, made of straw or other materials, to increase stability against horizontal loads, but other solutions can be considered and topological optimisation can be used. The students' various experiments initially focused on the arrangement of different bales with each other and gradually departed from the traditional techniques while retaining its fundamental principles, such as overlapping at least 30 cm between two stacked bales, for example.

Orienting the bales at a 45° angle significantly increases the wall's footprint on the ground, and thus its stability, while also providing an interesting texture and relief. This wall, dubbed the "Jagged wall," highlights the modular nature of the straw bale while incorporating it into a structural element with monolithic behaviour.

Fig 7. Jagged wall

Inserting curvature is another option for bringing stability to a load-bearing wall. Like Eladio Dieste for the Atlantida church in 1952, the students created a curved wall with an S-shaped footprint and a straight head. While the curvature does indeed bring a certain stability, the delicate balance between the staggered fitting of the bales and the lateral distribution of compressive forces proved less obvious. A few straps proved necessary to reinforce the wall against buckling and horizontal forces, increasing the capacity of the S-shape, which is subjected to tensile stress on the outer cord of the wall. This example enabled the students to see the limits of monolithic numerical modelling for a load-bearing straw wall, and to find a solution to overcome them.

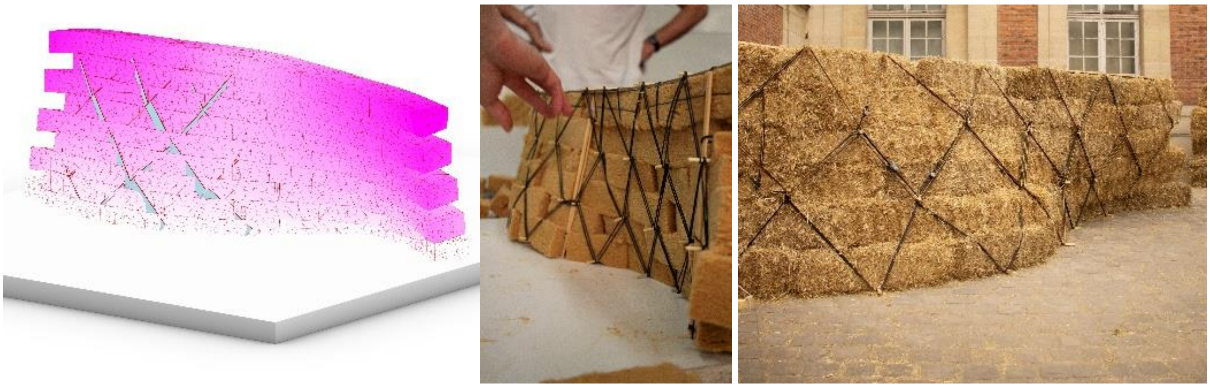

Fig. 8. S-shaped wall, from models to full scale

Another structural element to be studied was the column. Due to its high slenderness, this structural element is very quickly subject to buckling, which represents a major challenge. Indeed, the "classic" buckling of a monolithic straw column is increased by the geometric inaccuracies and non-planarity of the straw bales. A high degree of precision is required during installation, which is difficult to achieve.

Despite various attempts to increase inertia in both directions, the use of straw on narrow-width elements still quickly leads to the accumulation of excessive geometric imperfections, resulting in excessive moments and buckling of the element. Stabilization of the column using lateral tensioned elements and was tested, on the same principle as the sailing masts. Initially effective, the high creep of these elements under high compressive stresses led to rapid relaxation of the tensioned elements. Regular monitoring and calibration are required to maintain the stability of the whole column.

4.2. Structural capacities and horizontal elements

Next architectural part to be studied are horizontal elements: beams and floors elements, which work mainly under flexion. The challenge is to absorb the tensile forces (usually on the bottom chord of the element) that straw cannot. As for reinforced concrete, the idea was to use elements with high tensile strength, while saving materials. Metal cables and straps were chosen, and wooden bars and plates were used to brace the tensioned elements. The principle of mixed trussed beam was adopted. Several types were developed and tested.

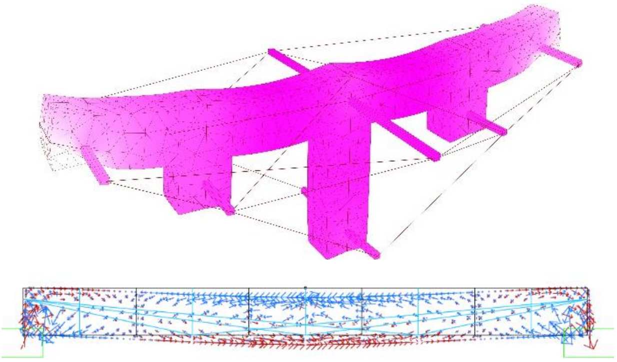

Fig. 9. Trussed beam models (Karamba models)

For straw bales to operate efficiently in compression, applying a prestress on the staw bales, is necessary prior to the prestressing phase. Given the slender dimensions of the straw element that composes the top chord of the truss, it is likely that the straw will buckle under a too high compression and because of the geometric imperfections. As for the columns, lateral support during this phase, before the elements reach their full compression capacity, is important. Lateral bracing under definitive state will also help against potential buckling. Due to the flexibility of straw, a beam requires a significant amount of inertia to achieve adequate resistance capacity, thus necessitating a considerable height.

For the slab, considered as a succession of beams, dimensional constraints quickly became even more limiting. Wooden reinforcement elements were therefore added to create a multilayered element. Straw eventually became the web element between the top and bottom chords of the wooden flanges. In addition to its structural role, straw is a good insulator, making it an interesting lead for development.

4.3. From a test pavilion to the Archifolies

As a whole, these parallel experiments provided valuable data for discussion on the structural performance of straw and its designing methods, and formed an exhibition showing all the different architectural parts that were tested. As they were gathered to design a first test straw pavilion, full-scale, at the end of the workshop, the students were able to focus on highlighting the straw potential. Straw has proven to have great potential under compression in massive geometrically optimised arrangements to avoid any buckling and distribute the geometrical imperfection inherent in straw. In each instance, tension element are needed for prestressing but as soon as traction or high flexion is involved, an interesting lead is to mix it with more tensile elements to reinforce it and enhance its potential.

Fig. 10. Perspective of the Archifolies straw pavilion, integrated the Jagged wall example

The construction of this first full-scale pavilion was an enriching and formative experience, full of learning, allowing us to glimpse new challenges in straw construction and continue to explore this material.

Fig. 11. First full-scale prototyping

For the Archi-Folies 2024, 20 French architecture schools are each paired with a French Federation of an Olympic sport, in order to build a pavilion that will be exhibited in Paris La Villette during the summer 2024 and the Olympic Games. Being paired with the French Riding Federation is the opportunity to build again a straw pavilion, 50m², displaying the equestrian sport and promoting straw construction by showing it in its most natural form.

Strong from the previous learning from the ‘Intelligent Fabrication 2023’ workshop, the straw is used in its massive form to create 3.2m high bearing walls. The Jagged wall experience, which proved to be the most successful result of the workshop by combining structural behavior and architectural texture, is slightly twisted and integrated in the design of the walls of the pavilion. A light reciprocal timber structure is preferred for the roof to span the 8m separating the walls while liberating the wall from high stresses and enabling to play with wide openings. As the pavilion is designed, realized, and mounted by students with limited on-site resources and limited time (1 week), the prefabrication and assembly strategy is fully integrated in the design process. Keeping the raw straw bales visible in this pavilion is a strong architectural point of the project to highlight and enhance the material and that remains possible since the pavilion is only temporary. In other cases, an additional protection to fire and rain would be needed and would raise other architectural questions related to straw design.

5. Conclusion

As a logical continuation of the research on concrete and prestressed stone, the "Intelligent Fabrication 2023" workshop underscore the turning in the fusion of cutting-edge technologies and ancestral materials, such as straw, in contemporary construction. The joint exploration of artificial intelligence, digital tools, and the materiality of straw enabled participants to push the boundaries of architectural creativity. By challenging established conventions and adopting an experimental approach, the workshop revealed new possibilities for integrating ecological materials into architectural design.

The workshop's pedagogical focus was crucial, providing students with a hands-on understanding of structural concepts such as tension, compression, and bending. The malleability of straw made these structural behaviours easily observable, reinforcing the educational value of the material. Despite the challenges associated with bio-sourced materials, this experience helped students grasp the inherent constraints of using such materials in sustainable construction.

Additionally, the digital tools employed during the workshop played a vital role in enabling students to comprehend and analyse the structural phenomena of their projects. These tools, despite their approximations, facilitated widespread understanding and appreciation of complex structural concepts.

This experience also highlights the importance of ongoing research on bio-sourced materials and their adaptation to digital design tools. By understanding the structural and behavioural properties of straw, participants were able to rethink design and modelling methods to address contemporary challenges in sustainable construction.

Ultimately, the "Intelligent Fabrication 2023" workshop demonstrated the potential of interdisciplinary collaborations and bold exploration in the field of architecture and construction. By seamlessly integrating technological advancements and traditional knowledge, this hybrid approach paves the way for significant innovations in the design and realization of sustainable buildings fit for the future.

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