Cardboard as a construction material for temporary architecture: a case study

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The topic of this article is cardboard as a construction material for temporary architecture: a case study of the Zbigniew Herbert Exhibition Pavilion. The Pavilion was designed and built by a group of 18 students at the course ProtoLAB at the Faculty of Architecture at Wroclaw University of Science and Technology in July 2018. The project focused on constructing Pavilion components out of paper tubes and corrugated cardboard, which have been proven to be a promising building material. Wood-based materials also were used to strengthen the construction. The design of the Pavilion aimed to use the geometry of the components to minimize the amount of metal used to connect elements. The article focuses on the problems of paper's strength, stability, connections, impregnation, and the way they have been solved during the building process. It also discusses the topic of the possibility of using the unimpregnated cardboard in outdoor constructions. The structure was then evaluated after 5 months of being used and exposed to diverse weather conditions. Damages in the Pavilion elements are mentioned in the paper and the probable reasons why they have appeared are explained. Conclusions from this article may be useful when designing similar objects in the future.

Keywords: temporary architecture, cardboard, exhibition pavilion, paper tubes, experimental structure

Introduction

Paper as a building material

In spite of being an inherent part of everyday life, paper is not usually considered a valid building material because it is believed to be unstable, fragile and not resistant to weather conditions. Cardboard could nonetheless be successfully used in architecture, especially in temporary structures such as pavilions or emergency shelters. Paper is natural, ecological, affordable, light, and easy to operate without the need of using any heavy equipment. As paper architecture is still a very new and developing area, every new structure is an experiment that requires testing, prototyping and searching for better solutions.

Paper-based pavilions

Paper is a material that has a chance to respond to the requirements of today's buildings related to the sustainable development and temporary character of architecture. For this reason its properties are studied in many scientific centers, including Kyoto University of Art and Design (research conducted by Shigeru Ban, from 1985), Delft University of Technology (research project *Cardboard in Architecture*, 2003-2005 [1]) and Technical University of Darmstadt (research project *BAMP! – Building with Paper*, 2017-2020 [2]).

Simultaneously with academic research various attempts of creating experimental paper buildings appears, including temporary, outdoor exhibition pavilions. In 2008 WORK Architecture Company designed in the courtyard of the PS1 Contemporary Art Centre in New York a structure called Public Farm 1 (see Figure 1). It was an Urban Farm made of paper tubes, which, supported by wooden discs and steel rings, worked both as construction and plant pots [3,4].

In 2015 the Kyotographie Paper Tube Temporary Pavilion was built in Kyoto by Shigeru Ban Architects. The frame structure was created from paper tubes with a diameter of 330 mm supporting the wooden construction of the polycarbonate roof (see Figure 2). The structure was used for a temporary photo festival exhibition. [5]

In the same year, the Exhibition Pavilion of the Wroclaw University of Science and Technology was built by

Figure 1. Public Farm 1 [4]

Figure 2. Kyotographie Paper Tube Temporary Pavilion [5]

Figure 3. Exhibition Pavilion of the Wroclaw University of Science and Technology [7]

Jerzy Łątka, to celebrate the 70th anniversary of the University. The Pavilion was composed of 36 arcs of laminated wood with impregnated paper tubes attached to them, creating a soft, rhythmic composition. The tubes with plexiglass circles were used as stiffening elements and exposition boards (see Figure 3). The Pavilion was the first paper-based architecture structure made in WUST and the starting point for further research and next realizations [6,7].

Drawing inspiration and experience from these projects the Zbigniew Herbert Exhibition Pavilion construction process was planned in order to deepen knowledge in the field of paper-based temporary architecture and study different types of structures.

Design guidelines and ideas

ProtoLAB project guidelines

The aim of the project was to create an experimental ecological mobile exhibition pavilion made mostly of paper elements which can be easily built using simple methods and tools. The Zbigniew Herbert Exhibition Pavilion was designed and built during the ProtoLAB course at the Faculty of Architecture at Wroclaw University of Science and Technology (WUST) by a group of 18 graduate students tutored by prof. Romuald Tarczewski and dr Jerzy Łątka. Students worked in teams of 3 focusing on various aspects of the project, such as structure or building materials and preparing themselves to the building process. The Pavilion was meant to be an architectural and construction experiment, a design challenge and a public facility dedicated to the memory of the Polish poet at the same time.

Initial ideas

The organic form of the Pavilion measuring 3 by 5 by 3 m was inspired by woodlands and divided into three sections: two bases on a plan of a curved triangle, slanted columns growing from the bases resembling tree trunks, and the roof symbolizing tree crowns with fluttering foil strips as leaves. Geometrically the Pavilion was a cuboid with the construction grid with a 0.5 m spacing cut into parts by a parametric surface and expanded to create the bases and roofing of the Pavilion (see Figure 4).

Paper is generally an affordable and light material with limited strength and for this reason, it is usually used to create massive constructions that provide better stability. The Pavilion was an attempt to create an openwork framing form that requires the minimum amount of building materials. Bases and roofing were thus designed to be composed of flat perpendicular ribs with a 0.5 m spacing in between.

Research and project development

Changes in the form of the Pavilion

During the development of the project, it became clear that previously designed 6 columns would not guarantee the stability of the structure, so their number has been increased to 10: 4 vertical and 6 slanted (see Figure 4 point 4). To prevent the Pavilion from rain a polycarbonate roof was added (see Figure 4 point 1). To emphasize the organic character of the structure a decision was made to plant grass and flowers in the empty boxes of the bases. In some of the coffers of the roof, the polycarbonate plates in timber frames were added to serve as exhibition surface and the stiffening elements at the same time.

Choosing and testing the materials

The most common types of paper materials used as building elements are paper tubes, L- or U-shapes, corrugated cardboard, paperboard and honeycomb panels which were all considered for the purposes of the project. [8] After strength tests that had been carried out in the laboratory at the Faculty of Civil Engineering at WUST it became clear that the corrugated cardboard, in spite of being heavier than honeycomb panels, has a significantly higher compressive strength and will allow authors to design thinner ribs (see Table 1). As a result, the decision was made to construct the ribs out of 4 layers of 7 mm thick corrugated cardboard glued together with polyvinyl acetate glue. To

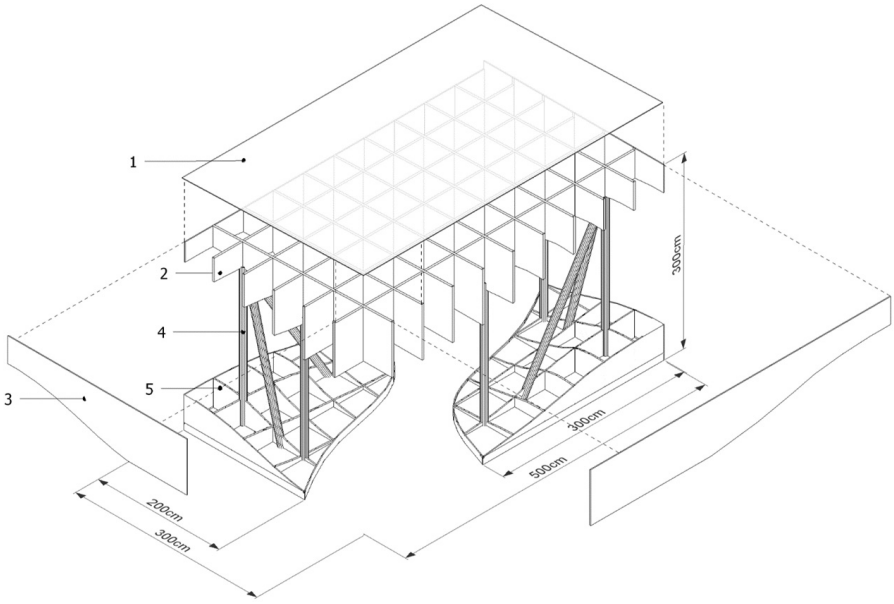

Figure 4. Axonometry of the Pavilion
1 – polycarbonate roof; 2 – sandwich corrugated cardboard roof ribs; 3 – side casings made of 4 mm thick plywood; 4 – paper tube columns
5 – bases ribs made of 18 mm thick plywood and OSB boards

Table 1. Selected results of compressive strength tests done by the authors in the laboratory at the Faculty of Civil Engineering at WUST, dimensions of samples: 5x15x30 cm, compression length: 15 cm

Type of material	Force [N/cm^2]	Weigh t [g]
honeycomb core panel 5 cm thick	12	60
honeycomb core panel 2 x 2.5 cm thick	17	70
corrugated cardboard 7 x 0.7 cm thick	71	125

strengthen the ends of the ribs and allow to fix the cover boards of the Pavilion's roof, elements of OSB boards were added, locally replacing two layers of the corrugated cardboard (see Figure 5).

The floor and the ribs of the base part of the Pavilion were made of 18 mm thick OSB boards and impregnated plywood boards and set on wooden beams due to the idea of making them a permanent element, which could later serve as a detached flowerbed. It was also crucial for the

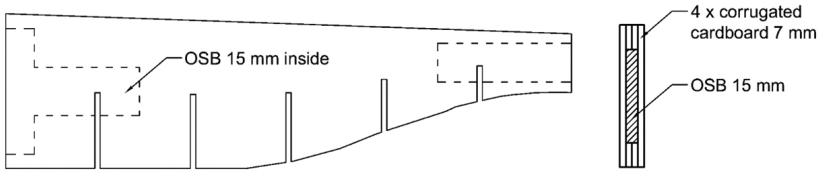

Figure 5. Sandwich cardboard roof ribs

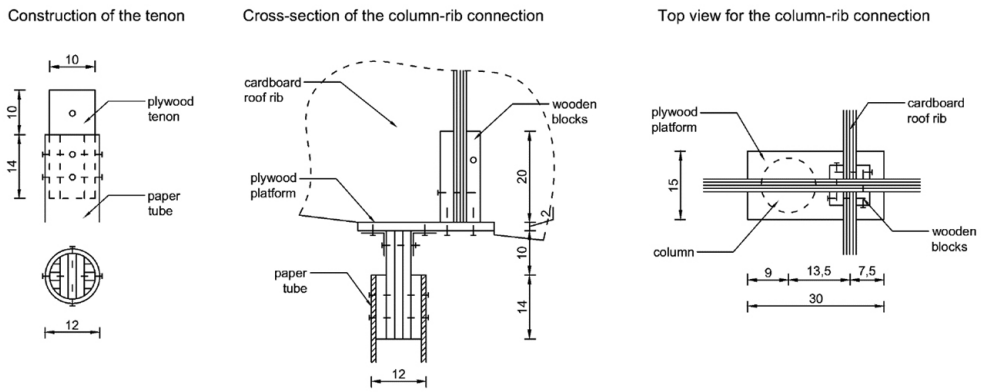

Figure 6. Column-roof rib connection

bases to have a substantial weight as the Pavilion has no foundations.

Paper tubes with an external diameter of 120 mm and 10 mm thick walls were used to create columns. They were connected with the other parts of the pavilion by the means of plywood tenons (see Figure 6).

Working on the connections

The Pavilion aimed to use the geometry of the specific components to minimize the number of used metal connectors and consequently reduce the weight and cost of the whole structure. All the ribs were prepared to be easily assembled thanks to the cuts on their edges and as a result, only small wooden blocks and screws were needed to stiffen the structure (see Figure 7). The bases of the columns were fixed to the wooden frame with 10 mm bolts working as hinges with metal plates. The roofing was attached to the columns by the means of plywood platforms (see Figure 6).

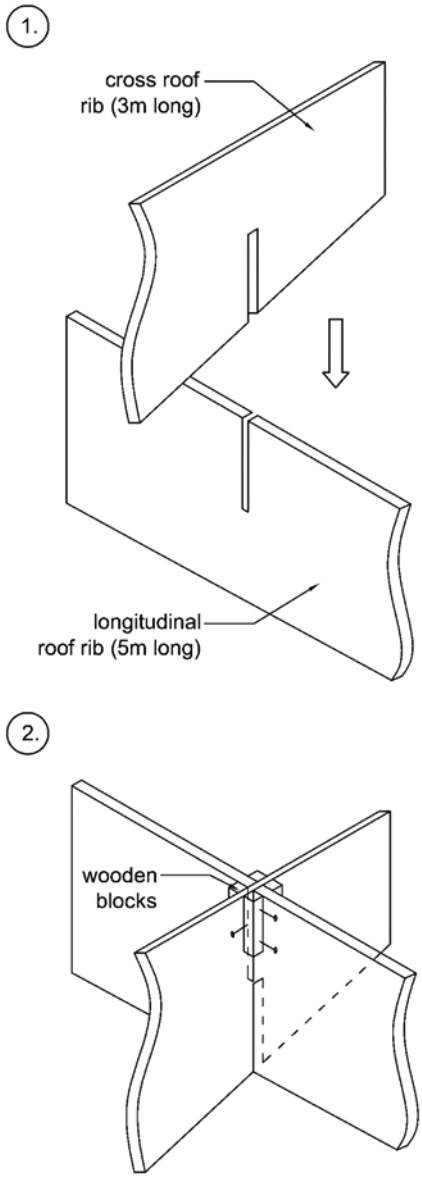

Figure 7. Roof ribs connection

Impregnation of paper components

Water and humidity are the biggest threat to paper-based structures, but an impregnated paper is usually not suitable for recycling. Having this fact in mind, a decision was made to impregnate only the columns, using the enamel based on polyurethane resins, silicone, and adhesive tape. The unimpregnated cardboard ribs were protected from water by polycarbonate roof at the top and the side casings made of impregnated thin plywood (see Figure 4 points 1 and 3). Its edges were also covered with adhesive tape.

Construction

Technology and schedule of works

The construction works lasted for 22 days with approximately 10 people working every day and were finished on 16 July 2018. Only basic equipment and materials were used and all the components made out of cardboard, OSB and plywood panels were prepared by students in a workshop (see Figure 8). The works began with preparation of the cardboard ribs, the most complicated and fragile parts of the whole structure. All the layers needed to be glued together with the OSB elements before the shape could be cut out. Later other elements were made and all the prefabricated components were transported from the workshop to the construction site.

The construction began with placing the two bases in the right positions, secondly, the columns were mounted and the four main roofing ribs were attached to them (see Figure 9). The remaining ribs and the casings were put into place afterward. Finally, the whole structure was stiffened and the finishing and the exhibition elements were mounted.

Problems and changes during the construction process

When the Pavilion was under construction, a heavy rain got the part of the ribs wet and they broke even though they were temporarily covered with a waterproof tarp. The

Figure 8. Preparation of the components in the workshop, photo by Jerzy Łątka

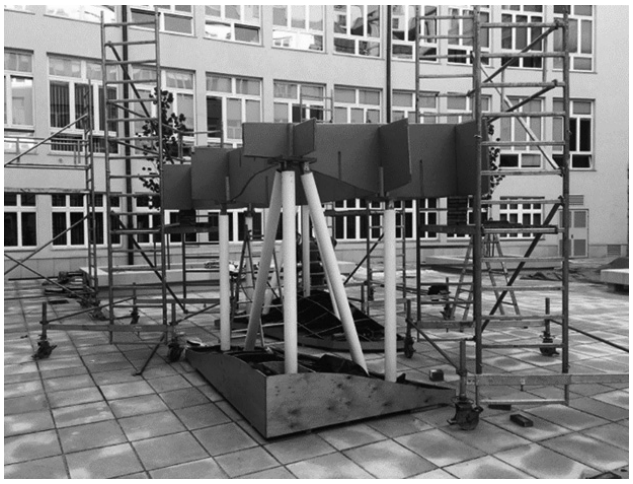

Figure 9. Under construction, photo by Jerzy Łątka

construction process had to be lengthened because of the accident and new ribs needed to be made. Due to the weakening of the ribs by putting the structure together and taking it back to pieces the decision was made to change the four main ribs from cardboard to 15 mm thick OSB covered with corrugated cardboard on both sides.

Conclusions and adjustments after construction

Immediately after completion of the work, it was raining in Wroclaw continuously for 4 days. This extreme weather conditions helped to expose the imperfections of the structure and allowed the building team to solve them before they could cause the destruction of the Pavilion.

The additional works included installation of a small aluminum gutter to move water away from the side of the Pavilion since the eaves of the polycarbonate roof turned out to be too short to do this. Furthermore, the second layer of enamel was added to one of the columns which started to absorb water. After this works the Pavilion was left for testing and observation in terms of stability of the structure and resistance to weather conditions.

Evaluation after 5 months

Surroundings of the structure and weather conditions

The most extreme weather condition recorded in Wroclaw during the 5 months of the experiment, between 20 July and 20 December 2018, were as follows. [9]

- Maximum temperature: 34°C in August
- Minimum temperature: -5°C in November and December
- The highest level of relative humidity: 90% in December
- The highest rainfall level: 24 mm in September
- The strongest wind: 47 km/h in October

The Pavilion is located in the closed courtyard with dimensions of approximately 30 by 45 m surrounded by a five-story University building. Because of this location, the actual maximum temperature near the Pavilion might have been higher and the strongest wind weaker than the aforementioned.

Expectations

The Pavilion was designed as a temporary structure with the expected lifespan of 3 to 4 month. Due to the problems that occurred during the construction a possibility appeared that it could be even shorter.

Structure condition after 5 months

At the time of writing this paper, the Pavilion has already been exposed for 5 months in diverse weather conditions. The structure remains safe and stable, although several demerges in cardboard components due to the wind, water, humidity and the weight of the roof can be noticed.

- On some of the columns, small damages to the enamel coating were visible just a few weeks after the construction, especially on the edges of the cardboard strips which have been used to produce the tubes. One of these damages provoked local crack in the outer layer of the cardboard (see Figure 10). Probably the single layer of the enamel had not isolated the paper tube completely from changes of air humidity and the enamel was not elastic enough to withstand the gentle shrinking and swelling of cardboard. Despite this, the damages are not severe enough to cause soaking cardboard and the columns are still dry and durable.
- The whole Pavilion is slightly leaning, which can be noticed by observing the columns that are no longer completely vertical (see Figure 11). The remaining corners of the roof are situated about 2 cm lower at the moment of evaluation than initially. The structure remains stable after the settlement.
- The surface of the unimpregnated corrugated cardboard ribs is visibly wavy because of air humidity (see Figure 12).
- The ends of the ribs located along the eaves of the roof get sometimes temporary wet during a longer period of

Figure 10. Damages in enamel coating on the columns

Figure 11. Position of the columns

Figure 12. Damages of the cardboard ribs

rainfall (see Figure 12). Nonetheless, the ribs retain their structural function thanks to the parts made of OSB inside them.

- The wooden parts of the Pavilion have signs of contact with water too, especially near the edges, screws, and staples. The 4 mm thick plywood of the roof casings has got wavy because of moisture. Also, some of the exhibition elements of foil strips have detached or got torn.

Nonetheless, the Pavilion is after 5 months in the significantly better condition than it had been expected after the construction (see Figure 13). The grid construction system with slanted columns and specially designed connections between them work as predicted. The structural elements remain their strength which allows the structure to be safely left for further observation.

Conclusion

After construction

The Zbigniew Herbert Exhibition Pavilion, which was exposed in the courtyard of the WUST A-1 building (see Figure 14), is another proof that paper elements can be successfully used as a building material, especially in temporary structures. The construction was simple enough to be easily assembled by students using only basic equipment. It is light, ecological, stable, and waterproof. The whole building process required considerable commitment and hard work. It was nonetheless a unique opportunity for students to acquire skills such as group work, project management, creativity in designing and use of materials. [11]

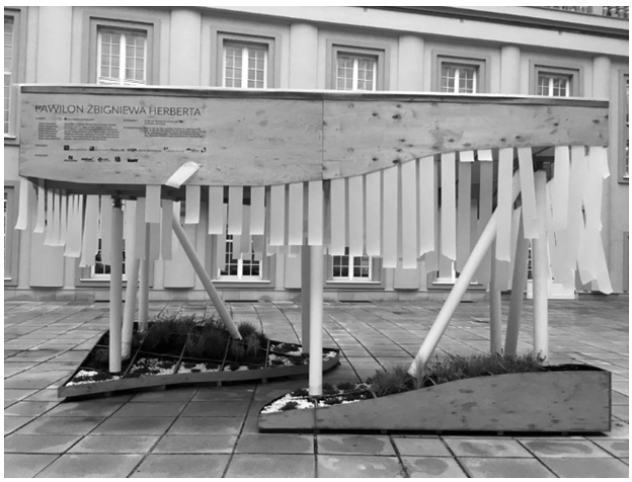

Figure 13. The Pavilion in December 2018

Evaluation after 5 months

In spite of the problems that occurred during the construction process, after 5 months of observation, the life span of the Pavilion exceeded the original expectations of the authors. Although some damages due to the humidity can be seen over the time the whole structure works properly and remains stable. The Pavilion proved that unimpregnated cardboard can be used even in construction exposed to atmospheric conditions, which make them easier to recycle and more pro-ecological

As the conclusion from the construction of the Zbigniew Herbert Exhibition Pavilion, in similar projects planned in the future particular attention should be paid to the following issues.

- The level of elasticity of enamel used for cardboard impregnation and the number of its layers.
- The size and location of eaves, gutters, casings and other elements physically protecting cardboard from rainfall.
- The use of thin plywood without additional stiffening layer.

Future plans

The Pavilion is supposed to stay in the courtyard of WUST A-1 building under further observation. It will be probably taken to pieces and recycled in spring 2019 and the conclusion from this experiment will contribute to the development of further projects using paper construction elements.

Figure 14. The Pavilion in the courtyard of A-1 building of WUST, July 2018, photo by Jerzy Łątka

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Acknowledgment

The Pavilion was designed and build thanks to tutors: Prof. Romuald Tarczewski and Dr. Jerzy Łątka and students: Szymon Ciupiński, Joanna Gronostajska, Eżbieta Kłeczek, Konrad Niedźwiedziński, Paweł Balcer, Agata Witczak, Patrycja Jędra, Damian Kuna, Wojciech Wiśniewski, Małgorzata Zielonka, Maciej Marszał, Malgorzata Denysiuk, Monika Smorąg, Yuri Zabuzhko, Agnieszka Owczarek, Justyna Kaźmierczak, Jolita Tamošiūnaitė and Agata Jasiołek. The realization of the project was possible thanks to cooperation with Wroclaw University of Science and Technology, Faculty of Architecture, students' organization Humanization of the Urban Environment, archi-tektura.eu, Czasoprzestrzeń, Centrum Przedsiębiorczości i Biznesu Dąbie, Wolne Meble, Accredited laboratories at the Faculty of Civil Engineering and the financial support of Schumacher Packaging, BART Packaging, Dekoral Professional and Grunwald24 printing shop. This paper was written thanks to the support of Jerzy Łątka.