Paper relief architecture.

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Abstract
The article presents two contemporary projects of paper structures relief architecture designed and built by Shigeru Ban Architects and Voluntary Architect Network. Author of the article took part in design and construction process of one of the projects. The project of Yaan Nursery School, which was built from November 2013 till March 2014 is presented in comparison to another project realized by Shigeru Ban and VAN in the city of Chengdu after the Sichuan Earthquake in 2008. The article gives the introduction of paper components in architecture and its history and shows both projects with their differences as well as evolution of the approaches to structural solutions. The age difference between the projects is 5 years. The attempt of determination of the quality of paper as a construction material is made by comparison of their condition and the process of wear and tear of the older building. At the end of the article thoughts of the author about both projects, their implementations and pros and cons are presented.

Keywords: paper in architecture, relief, emergency architecture, paper tubes, Shigeru Ban Architects.

1. Introduction
The tradition of using paper in architecture is dating back to ancient China and Japan. The earliest example of paper partitions in the form of folding screens produced in China are dated to 8th Century A.D. The first mentions of such solutions comes from 2nd century B.C. Although, China is the country of paper origin, the Japanese highly developed techniques of paper making and made paper a common architectural application in form of Shoji (translucent paper screens), fusuma (sliding paper panels) and others.

Since paper was found in 2nd century B.C and spread by T’sai Lun a Chinese Minister for Agriculture two centuries later, the main idea of paper making stays still the same. Despite the machinery changed through the years and industrial paper making started in 1799 with the invention of Frenchman Luis Robert, paper is still a layer of vegetable fibres, mostly cellulose connected together in wet environment and then pressed and dried. Ease of production, wide range of raw sources and its properties make paper a material that is eco friendly, cheap and easy to get.

Thinking about paper in architecture we think about traditional Japanese architecture in which paper was used both as a decorative and functional component. Nowadays, the Japanese architect Sigeru Ban, known as a “paper architect” has the biggest number of works done with paper as a structural material. Shigeru Ban is also known for his engagement in relief architecture. Since 1995 he has led a non profit organisation Voluntary Architects Network, which has taken part in many different relief projects around the World. Activity of VAN as a non profit organization concentrates on research, design and erecting the emergency buildings. The volunteers engaged in the organization are mostly students of Shigeru Ban but also students and professionals who come from different parts of the World to participate in the projects.

However, the shelters and houses designed with paper as a main material have a longer history. First known examples of building made out of paper was shown at the Great Fairs in Paris in 1867. The company ADT from Pont-a-Mousson, showed prefabricated houses made out of paper at the exhibition: summer house with the dimensions of 6 by 8 meters, hospital of 5 meters wide and 3 meters high, and about 20 meters long and 5 meters wide prefabricated house for warm countries. The houses were built of 3 m long and 60-80 cm wide paper boards, with U shaped intersection. The wall was constructed of two 4 mm thick paperboard with 10 cm void in between. The weight of hospital paper structure was about 92 kg per m of the elevation[5].
There were several different propositions of paper houses in the XX century including: Emergency Shelters made by US Institute of Paper Chemistry in 1944 with the dimensions of 2.4 by 4.8 meters and weight of 500 kg, which could be erected by one man in one hour, the dome-like construction consisting of 24 elements of plastic coated paperboard invented in 1954 by Container Corporation of America as well as university research projects, mainly conducted in USA, Great Britain and Germany.

The above experimental buildings show that paper in form of paperboard as well as paper tubes or honeycomb panels might be successfully used as a temporary shelter for victims of natural disasters or human activities such as wars or eviction. The first samples of it showed up almost 150 years ago and the process of finding the architectural and structural solution for such buildings is still conducted in factories, companies and universities around the World.

2. Case studies:

In 2008 and 2013 a big earthquakes occurred Chinese province Sichuan. Shigeru Ban together with Voluntary Architects Network designed and built temporary educational buildings. In 2008 the Hualin Primary School was built, five years later Yaan Nursery School. Both have structure based on paper tubes. Both have similar functions and were built in the same climate conditions. The distance between Chengdu and Yaan is approx. 130 km. Differences in the structure and design approach are the results of the conditions associated with realities of the place, funds, cooperation with local companies and architectural offices as well as evolution of the design.


Figure 1: Hualin Elementary School, photo taken in 2013 source: Jerzy Łątka.

After the big Sichuan Earthquake that occurred on the 12th of May 2008 Chengdu, the capital city of the Sichuan Province, Shigeru Ban contacted professor Hironori Matsubara who taught at the same university as Shigeru Ban - Keio University in Tokyo and also was a building consultant in Beijing. A month later Shigeru Ban with the volunteers from Banlab at Keio University and Chengdu Southwest Jiaotong University presented a prototype house for the victims of the earthquake. At the same time Chinese government started the program of building temporary houses for those who lost them in the earthquake. Although Shigeru Ban lost the chance to build the houses, he agreed to the request of local NGO “Rebirth of Environment” and Chengdu Chenghua Elementary School to design and build a temporary elementary school in Chengdu’s Hualin district.

Shigeru Ban prepared the proposition of three oblong pavilions, each of which contained three classrooms with desired dimensions of 9.7 by 6 meters per classroom. One of the classrooms was divided into two rooms to
provide a space for administration and educators. The dimension of each pavilion is 29 by 6 meters with another 1.5 meter wide exterior, covered corridor.

The request from Education Bureau was to complete the construction before September when new semester started. During the design process the demolition of existing and damaged class rooms was undertaken. Retained foundations of the destroyed school was used as a foundations for emerging construction.

The buildings were built by students of Keio University in Tokyo, Chengdu Southwest Jiaotong University as well as volunteer teachers of the school. 120 volunteers were divided into three teams and in order to complete the structure before new school year there was a competition for the best and fastest team announced. All three building were built in 40 days.

2.2 Yaan Nursery School. Shigeru Ban Architects, Voluntary Architects Network, 2014

![Figure 2: Opening Ceremony of Yaan Nursery School in April 2014, source: Shigeru Ban Architects](image)

On the 20th of April 2013 the big “Yaan earthquake” occurred in the Sichuan province in China with the magnitude of 7 in the Richter scale. Shigeru Ban, who had built temporary, paper structure of Hualin Elementary School after another “Sichuan Earthquake” in Chengdu, five years earlier, went to China to check if his structure was not damaged. The Hualin School, built in 2008 survived unaffected. During the trip Shigeru Ban visited small town Tai Ping near to Yaan city. The town was destroyed in approximately 70%. Shigeru Ban decided to design and build a kindergarten for the youngest citizens of the town. The architect invited his students from Shigeru Ban Studio at Kyoto University of Art and Design, among them the author of this article, who was conducting there a research on paper as an architectural material. Design team consisted of arch. Yasunori Harano, assistant of Shigeru Ban at Shigeru Ban Architects and KUAD University, arch. Mirian Vacari, Brazilian architect interested in paper architecture, arch. Jerzy Łątka and students: Alexander Riva, Yuta Sakurai and Hoshi Kazufumi.

Design intent was to erect temporary building on a plan of 3 by 3 meters grid. The dimensions of the building are 21 meters long and 6 meters wide. The building is divided into two classrooms with the interior corridor with main entrance between. First idea assumed the spacing of the columns on a grid of 3x3 meters, but later school teacher decided that middle columns would interfere in conduct of children activities. Middle columns were removed and structure was calculated again in order to obtain a structural stability.

The design process was finished in September. The author, who had already gone back to Poland, received the invitation to the building site in Chengdu and went there in November for a month. There were about 15
volunteers already involved in the project divided into two groups. One group went to Tai Ping and another one stayed in Chengdu. First weeks were devoted to work on foundations at the building site, impregnation of paper tubes and preparation of wooden joints in Liu Yang Architect workshop in Chengdu. The wooden joints were made by second group of volunteers including the author. After two weeks of preparation when all the wooden elements were prefabricated and all the necessary components like insulating foam, roof cladding, perforated L-angles etc. were bought, the volunteers went to Tai Ping. After levelling of base joints (joint B), the erection of paper tube structure started. Paper tubes were impregnated in advance by dipping in polyurethane liquid. The erection itself would be a very fast and easy process, especially that project was designed in such a way as not to use any crane. Unfortunately some new problems appeared, which delayed the construction process, such as wrong colour of steel elements or incorrectly threaded bracing elements. After two weeks at the site the paper tube structure was done. The next weeks were devoted to the roof structure, installation of wall panels, interiors and landscaping. The building was opened to the public on the first of April 2014.

3. Discussion
In this part the author compares both buildings constructed in the same area (Sichuan Province) with a difference of five years. Author focuses on architectural details and on the comparison of better and worse aspects of the performed constructions.

3.1 Structural systems.

Figure 3: Axonometric view of paper tube structure and bracing rods of a) Hualin Elementary School and b) Yaan Nursery School, source: Shigeru Ban Architects,

The structural system of the Hualin Elementary School is based on transverse frames built of paper tubes. Each of the three erected building has a dimension of 6 by 29 meters and consist of 13 transverse frames. Each frame was constructed of 4 paper tubes with the dimensions of 240 mm outer diameter and 18 mm thickness of the wall connected longitudinally with another five paper tubes with the same size. Vertical paper tubes that support the walls are 2200 mm high, diagonal paper tubes for roof structure are 3120 mm and longitudinal paper beams are 2200 mm long. The paper tubes of transverse frames are connected with wooden box-shaped joints with studs on which paper tube are slid. The joints were ordered in local factory. After they arrived it appeared that they were empty inside. Some extra reagent had to be used to fulfil the joints and make them strong enough.
In Yaan Nursery School the structural system consists of paper tubes that play a role of columns and beams. Roof structure is a mix of timber and steel perforated L-angles. Paper tube structure was built out of 49 paper tubes with the length of 2617 mm, the outer diameter of 234 and 15 mm thickness of the wall. The whole structure was strengthened with horizontal and vertical bracing rods. The new structural solution, that Shigeru Ban wanted to use in Yaan Nursery School was dictated after the problems with which the architect had to struggle during the construction of Hualin Elementary School in Chengdu in 2008. To avoid this risk, Shigeru Ban had proposed cross-like wooden joints made out of laminated timber boards.

3.2 The joints of paper tubes.

In the project from 2008 the architect’s intention was to design a structure which was easy to erect by non-professionals like students or volunteers. There are four different types of the joints. The top joints that connect the rafters and columns are designed as wooden blocks with off standing arms in the shape of octagons on which the paper tubes were slide and fixed with 12 mm bolts with nuts. The off-standing arms are placed at an angle of 125° for joint A between rafters and 118° for joint B between rafter and column. The joints for beams in the middle of the rafter are composed of two 18 mm laminated plywood boards. The bottom joint is composed of rectangular base with octagonal pin and T- shape steel plate on the bottom, which connects the joint to the foundation with anchor bolts. The joints were designed in a way to facilitate the installation of the frame on the ground and then by raising the whole frame with ropes and men power to connect it with another, already built frame. The bolts that fix paper tubes in a position go through the paper tubes and octagonal pins and are tightened from outside with nuts. Thanks to octagonal shape of the pins it was very easy to position the holes for bolts. The joints are compounded of four parts fastened with glue and still rod with diameter of 12 mm. They were ordered in the local factory and as author mentioned before they arrived empty inside. It was necessary to fill them up with some extra extender to make them strong enough.

Figure 3: Axonometric view of wooden joints, Hualin School: a) joint A, b) joint B, c) joint C, Yaan Nursery School d) joint C, e) joint D, source: Shigeru Ban Architects
The project of Yaan Nursery School assumed new constructional solutions of the wooden joints. This time, to avoid problems with local factories, the architects decided to design joints that would be prepared by volunteers in local workshop. Therefore they had to be simple in manufacturing. There are four types of wooden joints, bottom joint A for base of the column, upper joint B for connection between columns, beams and wooden structure of the roof, located at the side of the building. Joints C and D for middle connection of the paper tube beams and steel structure of the roof. Joint C and D differ only by having pin for the columns, joint D lies on the column, joint C hangs. Joints B, C and D are compounded of two flat elements inserted into each other in a way that gives a form of cross with four arms at an angle of 90° in view from the top. Joints are made out of laminated timber with the thickness of 72 mm. This type of joints allowed a significant reduction in the weight which resulted in the possibility of connecting joints and tubes in the air. Joints were fixed together with L shape steel plates which were used as a place to attach horizontal and vertical steel bracing. Although the joints in Yaan Nursery School use less material and are lighter and easier to produce they make all structure much more complicated with additional steel plates and necessary bracing.

3.3 Foundations.

In Hualin Elementary School the foundations of previous, damaged by earthquake, school building were used. The concrete slab was cleaned and prepared during the design process. However the foundations are too low and during the rains water can reach the wooden base joint. This resulted in capillary raising of water and the transfer of it to paper tubes. The bottom parts of some paper tubes were damaged and had to be replaced with steel tubes as a consequence.

In Yaan Nursery School foundations are raised up to 440 mm from the ground level to prevent damage of paper tubes by water. Thus it was possible to make openings in the foundation wall and provide UFAD (Under Floor Air Distribution), to lower the temperature inside the classrooms. Steel plates which are installed beneath wooden joint A keep the bracing rods to provide the stability of the building.
3.4 Walls.
The walls in both buildings are made out of the same product PVC sashes with glazing. Panels were fixed to the paper columns through wooden battens screwed to the tubes. In Hualin Elementary School short side walls were built as a solid one, made out of painted white plywood boards with the thermal insulation in between. The wind loads are carried by those solid walls in cross direction. In longitudinal direction wind loads are taken by long paper beams and plywood panels lied on the paper tube rafters. The stiffness of the wall of Yaan building is achieved by horizontal and vertical bracing which is present in all spans of the building. Vertical bracings abut to the internal side of the walls.

3.5 Roof Structure.

Hualin Elementary School has a clear and simple roof structure. Diagonal paper tubes play the role of rafters. They are stiffened with five rows of paper tube beams and additionally by still bracing. There are plywood boards attached on the top of rafters which brings more stiffness of the structure in longitudinal direction. The boards have round cuts in the middle in order to reduce their weight. Over the plywood boards the insulation foam and corrugated plastic sheets are laid. The exterior corridors roof and eaves are constructed with timber beams and plywood.

Roof structure in Yaan Nursery School is the most complicated part of the building. It is a mix of wooden beams and perforated L angles. The angles were used in another Shigeru Ban project Atelier for Glass Artist built in Tokyo in 2006. The wooden rafters are connected with joint C or D by perforated L-angles with 35 by 35 mm and 3 mm of the thickness. The L-angles are arranged in pairs on both sides of the joints. Also the horizontal bracing rods go through the joints. On the rafters there is a MDF board layer, then purling and thermal insulation foam in between. Roof is covered with steel plates layer. Large eaves should provide safety of paper tubes against getting wet due to rain.

Both buildings described above have their own pros and cons. Definitely a big advantage of Hualin Primary School is easy and clear structure of paper tube frames that support walls and roof in the same time. Each frame was able to be built on the ground and then raised up with human power and ropes, which allowed for easy, convenient and fast assembling on the ground. Scaffolding was needed only for the moment of connection of the frames and for the roof finishing. Small amount of additional elements like steel plates or bracing allowed for a fast construction of the buildings. Wooden joints because of their complicated shape had to be manufactured in professional factory. The amount of the material used and a risk of bad performance as well as large weight are the negative traits of the building. Another downside of the buildings are foundations which are too low to the ground level and cause the risk of damage of paper tube structure as well as a lack of UFAD system. The solution might be achieved by using silicone or steel pads under the paper tube columns that would stop the transfer of the moisture from wooden joints to paper tubes.
On the one hand the advantage of the Yaan Nursery School are wooden joints with simple geometry which allowed to make them by volunteers out of common wooden beams. The joints are relatively light so the process of combining might be done in the air. The large eaves protect the paper tube against the rain and sunlight which could adversely affect the impregnation. The high foundations move the tubes away from the water flowing over the ground. On the other hand the wooden joint assembly required additional elements and the structure was needed to be stiffened by bracing. The roof structure is far too complicated. The thermal insulation used in the building is not enough.

The buildings were erected as a temporary structure for about 5 years. However the Hualin school is still in use and nothing indicates that it will be pulled down soon. Both buildings require a maintenance at least as often as wood, which means that every year the paper tube should be painted with impregnation. In the authors opinion both buildings should be insulated in a better way. The temperature in Chengdu during the winter can drop down to 5°C, in Yaan even more. Due to the humi climate the paper tube might be installed inside of the building. It would avoid the risk of damaging the paper tubes by water sun and physical impact.

In spite of above mentioned defects the paper structure buildings are important examples of the use of paper in relief architecture. The material is cheap and easy to produce so it is suitable for temporary structures.

Traditional usage of paper in form of newspapers or books is becoming less popular in favour of electronic media. Opportunity of development of papermaking industry might be found in the construction industry.

Acknowledgement.

Participation in research at Shigeru Ban Studio at Kyoto University of Art and Design as well as in the project and construction process of Yaan Nursery School would not be possible without the support of Wroclaw University of Technology, home university of the author, and funds obtained from the European Union’s Human Capital Program, National Cohesion Strategy.

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