4 Paper structures. Case studies

Good design can create strength from weakness

'Shigeru Ban: Paper in architecture' [1]

The examples of paper architecture presented in this chapter show the wide variety of materials and compositions used. The chosen examples are divided into two sections. The first section, entitled 'The History of Paper in Architecture,' embraces the projects realised from the late nineteenth century to the late 1980s. The examples provided in the 'Case Studies' section were assessed more thoroughly for their function, structural system, usable area, used material, connections and details of the structure (foundation, walls, roof), impregnation and lifespan. The chosen projects represent the most interesting solutions as far as structure and use of materials are concerned. Each of the examples described in this section presented an element of novelty in the world of paper architecture.

§ 4.1 The History of Paper in Architecture

The tradition of using paper in architecture dates back to ancient China and Japan. The earliest example of paper partitions in the form of folding screens produced in China date back to the eighth century AD. Although China is the country where paper was first invented, the Japanese later further developed paper-making techniques and made paper a common ingredient in architecture in the form of shoji (translucent paper screens), fusuma (sliding paper panels) and other parts of buildings (see Fig. 4.1.) [2]. It is said that most Japanese houses are made out of wood and paper. In the traditional way of life, paper was used for many applications around the house. As described by Mitsuhiro Ban in the Handbook on the Art of Washi: 'Differing from such non-organic material as concrete, steel and glass or such non-organic and hard material as synthetic resin, paper and wood once were living. Therefore, they respond to our inner psychology and speak to us with strong and silent words'. [3]

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Since paper was invented and disseminated by Cai Lun, a Chinese minister for agriculture in the Han dynasty, in the second century AD, the main idea behind paper-making has not changed much. [4] Despite the fact that the machinery has changed over the years and paper-making was industrialised in 1799 with the invention of the first model of the continuous paper machine by Frenchman Louis Robert, [4, 5] paper is still a layer of vegetable fibres (mostly cellulose), connected together in a wet environment and then pressed and dried. Thanks to its easy production, a wide range of raw sources, great variety of types and many properties, paper is a material that is eco-friendly, cheap and easy to produce.

FIGURE 4.1 Shoji (translucent paper screens) and fusuma (sliding panels) in Nazen-ji Temple, built in Kyoto, Japan, in the thirteenth century AD, 2013

In traditional Japanese architecture, paper was used both as a decorative and a functional component. Nowadays, the Japanese architect Shigeru Ban, known as a 'paper architect', has the largest number of works created with paper as a structural material. But shelters and houses mainly made of paper have a longer history. A few chosen examples of realised projects and prototypes are presented below in order to describe the development of paper in architecture throughout the years.

In the first half of the nineteenth century, a shift from artisanal to industrial paper production took place. In 1871 Albert L. Jones in New York invented corrugated cardboard as a packaging material. [6] This invention opened new doors for the paper industry. Between 1874 and 1882, corrugated board with one side glued and with both sides glued was patented in the United States. Soon afterwards, engineers and designers started making the most of this new invention in the paper industry by experimenting with cardboard and corrugated cardboard as building materials.

The first prefabricated houses made of cardboard were exhibited in 1867, at the World Exhibition in Paris. Buildings constructed by the Adt company from Pont-à-Mousson had different functions and dimensions. A summer house had an area of 6x8m, a hospital was 5m wide and 3m high, and a prefabricated house for countries with a tropical climate was 20m long and 5m wide (see Figures 4.2, 4.3 and 4.4). [6]

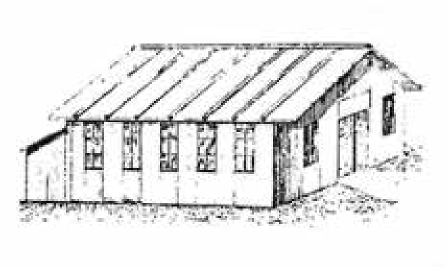

FIGURE 4.2 Prefabricated cardboard house, Adt, 1867

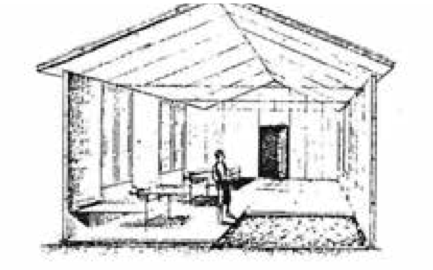

FIGURE 4.3 Cross section of the hospital made out of cardboard, Adt, 1867

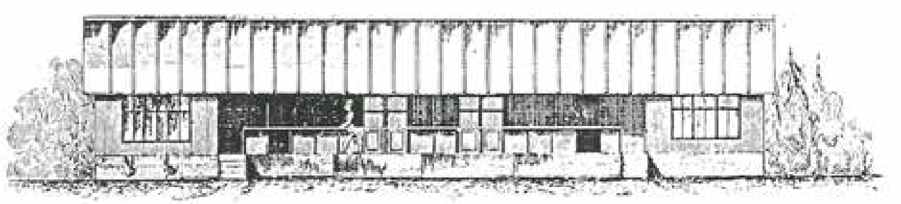

FIGURE 4.4 House for hot countries, made out of cardboard elements, Adt, 1867

The exhibited houses consisted of paper boards that were 3m high and 600-800mm wide, which were connected by means of U-shaped spacers. The construction involved double walls made out of cardboard (4mm thick) on either side of a cavity of 100mm. The hospital weighed about 92 kg per linear metre of the façade. Easily assembled but also easily blown away, it had to be anchored firmly to the ground.

One of the earliest examples of the use of paper in permanent architecture is a house built by mechanical engineer Elis F. Stenman in Rockport, Massachusetts, USA. He started building the summer house as a hobby in 1922. The house was completed in 1924 and Stenman spent all of his summers there until 1930. The house still exists and is open to the public. The structure of the house is a timber framework. The floor and roof were likewise made of wood. The walls were filled with pressed layers of newspaper glued and varnished on the outside. All of the furniture, except the piano and fireplace, were also made out of paper. Although in this case paper was used only as a wall filler, the Paper House is an example of the long-lasting durability of paper, which, with proper maintenance, has been in use for over ninety years now (see Fig. 4.5 and 4.6) [7].

FIGURE 4.5 The Paper House in Rockport, Massachusetts, USA, outer wall 1924

FIGURE 4.6 The Paper House in Rockport, Massachusetts, USA, 1924, detail of the wall

In 1944 the Institute of Paper Chemistry developed an experimental construction of sulphur-impregnated cardboard, which was intended as a portable expandable shelter for a one-year lifespan. The 2.40 x 4.80m large shelter (which only cost $60 and weighed 500 kg) could be set up by one man in an hour (see Fig. 4.7). The walls of the structure were made from waste paperboards formed in 25mm thick corrugated plates, soaked in sulphur and coated with several layers of fireproof paint. These emergency shelters were intended to last one year, but, as Sheppard et al. [8] wrote, were still standing 25 years later. In 1954 the Container Corporation of America, Chicago, developed a dome-like shelter from plastic coated hardboard (see Fig. 4.8). The 24 elements were held together with staples.

FIGURE 4.7 Experimental shelter by the Institute of Paper Chemistry, 1944

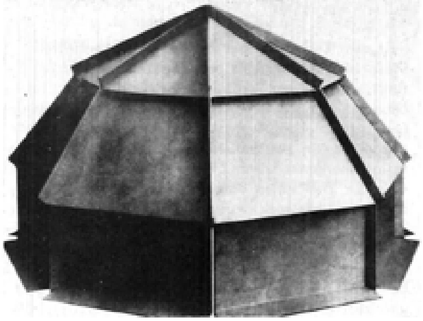

FIGURE 4.8 Container Corporation of America, dome-shaped house made of plastic-coated hardboard, 1954

Richard Buckminster Fuller, a pioneer of many building innovations, won the grand prize of the 1954 Triennale in Milan for a geodesic dome structure made of corrugated cardboard. Students of McGill University in Montreal, led by Richard Buckminster Fuller in 1957, built a construction featuring a geodetic division of space. The dome-shaped building has a diameter of 9.5m and was constructed from only two different standard elements. Those elements, a total of about one hundred pieces, were made of flat cardboard boxes covered on the outside with an aluminium sheet. The plates formed a shell-like outer skin (see Figures 4.9 and 4.10).

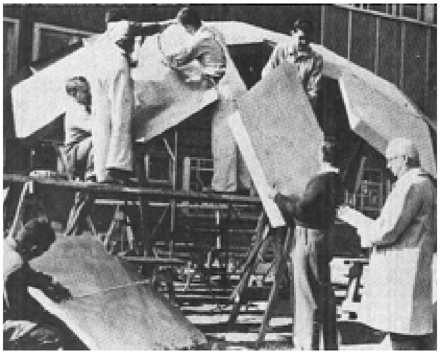

FIGURE 4.9 Construction at McGill University by students and Buckminster Fuller, Montreal, 1957

FIGURE 4.10 Dome shaped building by students of McGill University and Buckminster Fuller, Montreal, 1957

At the Architectural Research Laboratory of the University of Michigan in Ann Arbor, research was carried out between 1962 and 1964 on the use of cardboard laminated with polyurethane foam panels. It focused on the use of foam for the construction of buildings in developing countries. From this material, as well as other materials, frame members were formed with a triangular cross-section. The stress tests conducted on a two-storey test building proved to be sufficient in strength value.

Over one thousand accommodations called 'Plydom' with an anti-prismatic folded plate structure for seasonal farm workers in California were designed and realised by Sanford Hirshen and Sym van der Ryn in 1966. Those foldable units are highly economically sufficient. While open, their dimensions are 5.15x5.80m. The stability of the structure is achieved by parallel folds. The material used was a sandwich panel composed of approximately 10mm thick solid board on both sides with polyurethane foam in between. The board had been made waterproof by means of a polyethylene finish. The total cost of the unit (including heating, evaporative cooling, cooking, washing and complete furnishings) was $1,000 per item [6, 8, 9] (see Fig. 4.11).

In 1967 an experimental polyhedron-shaped construction designed by Keith Critchlow and Michael Ben-Eli was made of corrugated cardboard covered with chicken wire and then sprayed with a thin layer of concrete (see Fig. 4.12). The cardboard plates that were used as a formwork had to be protected from humidity during the concrete-covering process in order to ensure shape stability. The concrete was sprayed on in layers to reinforce and stiffen the cardboard structure before the final layer of concrete was applied.

FIGURE 4.11 Plydom – accommodation for seasonal farm workers in California, 1966

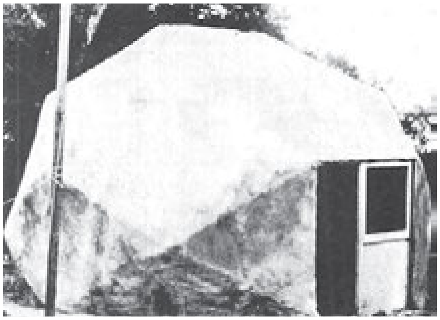

FIGURE 4.12 Experimental polyhedron-shaped structure of cardboard framework covered with concrete, 1967

The project of Baer Zome House features one of the earliest examples of a solar passive house, designed by Steve Baer in Corrales, New Mexico in 1971. The openable sandwich wall panels were composed of 50mm thick cardboard honeycomb panels laminated on both sides with thin aluminium sheets. The entire house consisted of clusters of zomes, whose name comes from a combination of the words 'dome' and 'zones' (see Fig. 4.13). Some of the walls were made of adobe blocks, and those exposed to the south consisted of 56-gallon steel barrels filled with water behind the glass and covered by openable sandwich wall panels to produce warm water. [10]

FIGURE 4.13 Baer Zome house, Corrales, New Mexico, 1971

Hong Lee and John Gibson, on the advice of John Zerning at the Polytechnic of Central London, developed a prototype for a prefabricated emergency shelter in 1974. An improved version of this, featuring three elements taken together, was exhibited in Wales for six months (see Fig 4.14). Similar principles were used by Vince Tickle and Hong Lee for a small student's house built over a car park. Three layers of corrugated board connected by means of bolts or stapling enclosed an area of 7.2x2.4m, with a height of 3.6m. The timber frame installed inside provided the necessary stability and contained a bunk bed on the second level.

At the experimental site of the California Polytechnic State University in San Luis Obispo, California, student proposals for emergency buildings were shown on the occasion of an 'open day' in 1977 (see Fig 4.15).

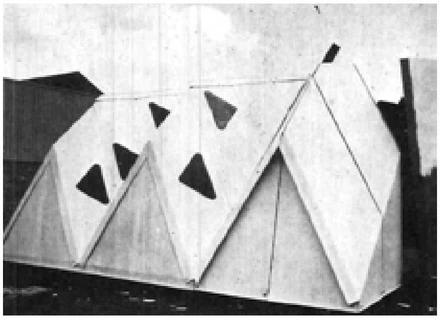

FIGURE 4.14 Hong Lee and John Gibson structure, 1974

FIGURE 4.15 Emergency building constructed by students of California Polytechnic State University, 1977

Developed by 3H Design (Hübner + Huster) in 1970, Pappedern was an 11.5m^2 or 16m^2 unit composed of 30mm thick corrugated board coated with fibreglass (see Fig. 4.16). Due to the limited lifespan (estimated to be one or two years), 89 units were

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used at the 1972 Olympics in Munich and Kiel, where they served as recreation and locker rooms, kitchenettes, first-aid rooms and toilets. The units were prefabricated, transported to the site by trucks and installed on the prepared foundations by crane. [6, 11]

In 1975, a 13x18m cowshed-like structure was built at the Instituut voor Mechanisatie, Arbeid en Gebouwen in Wageningen, the Netherlands. Its roof was composed of folded triangular cross-section beams, 9m long and 600mm wide, made of 95mm thick corrugated cardboard coated with polyethylene (see Fig. 4.17). To reduce the formation of condensation inside the cardboard, the cut edges were sealed with special adhesive tape. However, since the polyethylene lamination was not a complete barrier to water vapour, the cardboard was subject to diffusion. As a result, the shed suffered more from the humidity inside the building than from rain.

Another Dutch experiment with cardboard as a building material was an eco-house graduation project carried out by Paul Rohlfs at TU Eindhoven in 1975. After his graduation, Rohlfs received a temporary assignment to build a prototype. Several prototypes were built and examined. The walls of prototype No. 1 consisted of honeycomb panels combined with corrugated cardboard. Prototypes Nos. 2 and 3 were made of honeycomb panels with an exterior breather foil and interior vapour barrier. Prototype No. 4 was inhabited and survived the harsh winter climate of the province of Groningen (see Fig. 4.18). [12, 13]

These paper projects mar ked the end of the ‘prehistory’ of paper architecture in the 1970s.

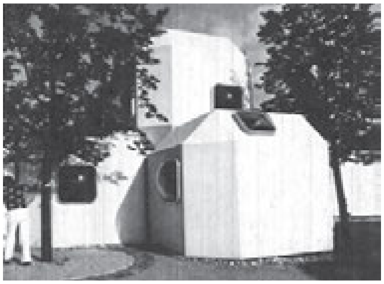

FIGURE 4.16 Cardboard units for the Munich Olympics by 3H Design, 1972

FIGURE 4.17 roof beams made at the Instituut voor Mechanisatie, 1975

FIGURE 4.18 Prototype of a cardboard house by Paul Rohlfs, 1975-1980

§ 4.2 The Modern History of Paper Architecture

In the 1980s, a new era of paper architecture began. It was the Japanese architect Shigeru Ban (born 1957) who had the greatest impact on the promotion of paper as a building material. Ban's adventure with paper in architecture started in 1985, when he was asked to design an exhibition for the architect Emilio Ambasz, who was an Argentinian by birth. He used screens made out of squared in section paper tubes and honeycomb panels cores to organise the exhibition space. In the following year, Shigeru Ban designed an exhibition in remembrance of the famous Finnish architect and designer Alvar Aalto. Both on account of his limited budget and because he wanted to include a reference to wood, which was one of the basic materials used by Aalto, Ban decided to use paper tubes in between the exhibits (see Fig. 4.19). Later, the architect decided to take a closer look at the tubes and examine the possibility of using factory-produced tubes as structural elements in architecture. Tests were carried out to examine the resistance of paper tubes to axial compression, bending and ripping by connecting members, such as screws. Furthermore, Ban carried out examinations of the changes paper underwent as a result of various climatic conditions. In 1991, the results of all this research allowed him to obtain permission for the first permanent construction made of paper tubes in Zushi, Kanagawa Prefecture, and to build Library of a Poet (see: Case Studies, section 4.2.1) .

FIGURE 4.19 Alvar Aalto exhibition designed by Shigeru Ban, 1985

The history of the use of paper in architecture shows a wide variety of experimental approaches. The invention of machine-produced paper, as well as of corrugated cardboard and honeycomb panels, had a significant influence on the development of paper-based structures. Most of the examples presented in this chapter can be categorised as emergency or short-lifespan houses. The housing shortage in America and Europe after World War II was one of the reasons why new materials and applications were given a boost in low-cost housing for immigrants and soldiers returned home from the war. Furthermore, experimental works created in the 1960s by Buckminster Fuller or Keith Critchlow and Michael Ben-Eli encouraged other designers to reach for paper and cardboard as new materials for architecture. Cardboard was used as both the primary and secondary structural material. Starting from 1980, more and more attention was drawn to sustainable materials. Since then, paper has been widely recognised as an eco-friendly material and gained popularity in architectural applications.

The milestone in contemporary paper architecture was Ban's Paper House project, built in 1995. The project was the first structure in which paper tubes were allowed to be used as a structural material for a permanent construction (see: Case Studies, section 4.2.3, Paper House).

The largest construction made of paper tubes was the temporary Japan Pavilion, designed by Shigeru Ban for the World's Fair Expo 2000 in Hanover (see: Case Studies, section 4.2.7). [14]

Over 55 projects designed by Shigeru Ban involved the use of cardboard as an architectural material. The nature of the projects varies according to their function (furniture, exhibitions, pavilions, educational and cultural, and relief buildings), lifespan (temporary and permanent) and specific materials. Most projects featured paper tubes, but sometimes honeycomb panels were used, as well.

In 2014 Shigeru Ban was awarded the Pritzker Architecture Prize, which is often described as the Nobel Prize for Architecture. The jury stated that the architect was presented with this highly prestigious award for his brave formal and functional quest in architecture, using new materials, and for his human and humanistic approach to his profession, among other things. [15]

Apart from Shigeru Ban, there are other contemporary examples of architects from all over the world using paper as a material in spatial structures. The earliest example of a permanent building with cardboard structural elements in Europe is Westborough Primary School in Westcliff-on-Sea, England. The building was an experimental design by Cottrell & Vermeulen Architecture, in association with BuroHappold Engineering, a

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consultancy and design agency. The social room for children was built in 2001 and is still in use fifteen years later (as of February 2016).

Professor Mick Eekhout, Chair of Product Development in Architecture at Delft University of Technology and founder of a Dutch company called Octatube, cooperated with Shigeru Ban during the realisation of three projects: Demountable Paper Dome for IJburg Theatre in Amsterdam and Utrecht, the Netherlands (2003), the Vasarely Pavilion in Aix-en-Provence, France (2006) and Paper Bridge in Vers-Pont-du-Gard, France (2007). In 2010 Professor Eekhout's son, Nils Eekhout, designed and built a multi-functional extension for the Ring Pass field hockey and tennis club in Delft in the Netherlands, using the Tuball space frame system of Octatube (1983) with cardboard tubes.

A recent innovation in paper architecture is Wikkel House. 'Wikkelen' is Dutch for 'to wrap'. Designed by René Snel in the late 1990s, Wikkel House was further developed by Fiction Factory, based in Amsterdam. In 2012 Fiction Factory bought the copyrights, (re)developed the project and commenced production of these wrapped corrugated board structures.

Impregnation and coating methods proved that many different materials, such as sulphur, fibreglass or polyethylene coating, cladding with another material, sandwiched compositions or spraying concrete on formwork-like cardboard structures, were successful. The ongoing process of experimental use of paper in architecture was provided a boost by new production technologies, new chemical compositions, and by the growth of the paper industry and market.

The aforementioned buildings – both the experimental ones and the ones that were actually realised – show that paper in the form of products such as paper boards, paper tubes and honeycomb panels can be successfully used not only as a part of the construction but as a main load-bearing element. In order to allow us to take a closer look at the structural possibilities of paper-based elements, we will study a few realised examples of contemporary paper architecture below.

By far the most popular cardboard-affiliated product in the built environment is the honeycomb-filled lightweight hardboard door with a timber frame for interior purposes. Millions of these doors have been produced and painted, and they are in regular use in houses and apartments.

The 150-year history of paper architecture shows that paper is an inspirational building material that provides ample potential for novelties waiting to be explored by industries, factories, companies and universities around the world.

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§ 4.3 Case Studies of paper in architecture

The following section will provide a closer look at a few selected realised structures, in which paper was used as a main structural material. Each project will be described in accordance to its function, usable area, structural system, composition (walls, roof, floor), details (connection between elements, connection with the ground) and method of impregnation. Fifteen case studies were chosen from the dozens of realised projects featuring paper architecture. The selected projects have distinctive qualities that will guide us to a better understanding of the properties of paper as a building material.

§ 4.3.1 Library of a Poet

Authors: Shigeru Ban Architects
Year: 1991
Location: Zushi, Kanagawa, Japan
Area: 35m^2 (size: M)
Lifespan: Permanent
Type: Housing

Library of a Poet is a 35m^2 extension to the House for a Poet, which was enlarged and renovated by the architect two years previously. Library of a Poet is the first permanent building in which paper tubes were used as a structural material. This one-storey building with entresol is composed of six paper tube truss supports which hold an arched roof also composed of paper tubes (see Fig. 4.20). The roof arches are tied with two horizontal paper tube beams post-stressed with steel rods inside (see Fig. 4.21). The paper tubes (100mm in diameter and 12.5mm thick) making up the walls were tested for one year to investigate the phenomenon of creep in different temperatures and relative humidity. A 400mm long specimen was inserted between two plates that were fastened by steel rods at 29 kg/cm^2, which was one-third of the maximum compressive strength of the paper tubes. For a period of one year, measurements were taken at intervals of about one week. The tests showed that paper tubes deformed depending on the different temperatures and levels of humidity, but deformation due to creep was minimal. The paper tubes were connected by 100x100mm wooden blocks braced with post-tensioned steel rods diagonally and inside of the tubes (see Figs. 4.22, 4.23). The paper tube structure was inside the building, where it was protected from the outside weather conditions by the roof and glazed walls. In other words, the tubes were not exposed to the weather conditions. The structure was

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placed on a concrete floor slab. The four full-height timber bookshelves were installed independently of the paper tubes on both longitudinal walls. The bookshelves were cantilevered from the floor and absorbed the lateral wind forces. They were also thermally insulated and finished from the outside, and so acted as external walls. This idea was later used by Shigeru Ban in his Furniture House projects. [1, 14, 16]

The structure used to create Library of a Poet was a hybrid structure consisting of paper tube trusses and prefabricated bookshelves. The tubes mostly carried dead loads and vertical loads from the roof, while the bookshelves carried the lateral forces. The combination of the two different structures allowed Ban to use relatively small tubes and connections. The paper tubes were connected by wooden blocks and post-stressed steel bracing, which meant no screw or bolt connections had to be used between the wood and the paper, because paper is quite fragile and will tear easily when used in such connections.

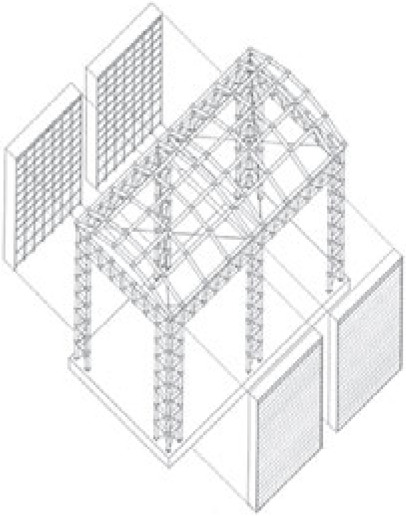

FIGURE 4.20 Exploded axonometric view of the structure of Library of a Poet, 1991

FIGURE 4.21 The library viewed from the inside, 1991

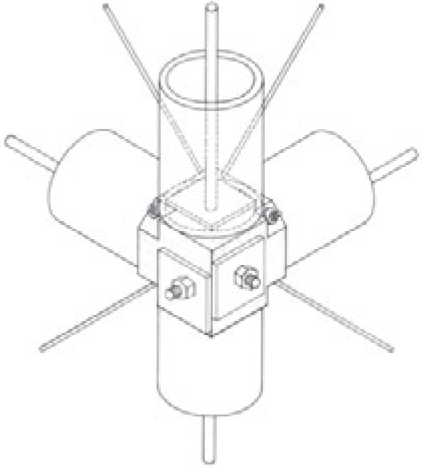

FIGURE 4.22 Axonometric view of a connection detail, 1991

FIGURE 4.23 Photo of a wooden connector of paper tubes and post-stressed steel rods, 1991

§ 4.3.2 Apeldoorn Cardboard Theatre

Authors: Prof. Hans Ruijssenaars, ABT Building Technology Consultants
Year: 1992
Location: Apeldoorn, the Netherlands
Area: 240m^2 (size: L)
Lifespan: Six weeks
Type: Temporary event venue

To mark the 1,200th anniversary of the first settlement of the city of Apeldoorn, Prof. Hans Ruijssenaars was asked to design a temporary theatre. As Apeldoorn is situated next to the Veluwe region, which has quite a tradition of paper production, Ruijssenaars decided to use paper as a material for his temporary theatre. The cylindrical shell that covered the area (12x20.5m) was composed of members made of corrugated board (see Fig. 4.24). Each of the members had a dimension of 1,200mmx350mm and was 35mm thick. It consisted of seven laminated layers of corrugated cardboard. At the end of each side of the member, the hardboard plates used for connections with nodes were laminated. Each node connected six members with a wooden ring and a hose clip. The interlocking connectors required only a hammer and screwdriver to keep the elements together (see Figs. 4.26 and 4.27). The triangular composition of members was covered with plasticised corrugated cardboard plates. The seams between plates were taped off. The whole structure, covered with a stretched canvas membrane that was designed to keep the structure watertight and was anchored to the ground with pegs, also kept the lightweight theatre in place and prevented it from being blown away (see Fig. 4.25). The canvas was kept away from the cardboard plates by the membrane stretched between the tops of the nodes. The semi-cylindrical theatre was placed on prefabricated concrete slabs. The bottom nodes were connected with timber beams by 50x6mm steel plates (see Fig. 4.29). The total weight of the 240m^2 theatre, which was able to accommodate up to 200 visitors, was 1,500kg. The structure was used for six weeks, i.e., not long enough for the impregnated cardboard elements to be weakened by moisture from humid air creeping into the material. [13, 17, 18]

Because the structure was mostly made of cardboard rather than other materials, the Apeldoorn Cardboard Theatre was a temporary structure that generated little construction waste after the end of its lifespan. The simple connections between the structural elements and their lightness made the construction a basic one. As the Theatre was only ever supposed to be used for six weeks, the construction elements were not impregnated. However, for a longer lifespan, corrugated members could be coated or wrapped with a layer polyethylene film or plastic foil to create a functional decoration.

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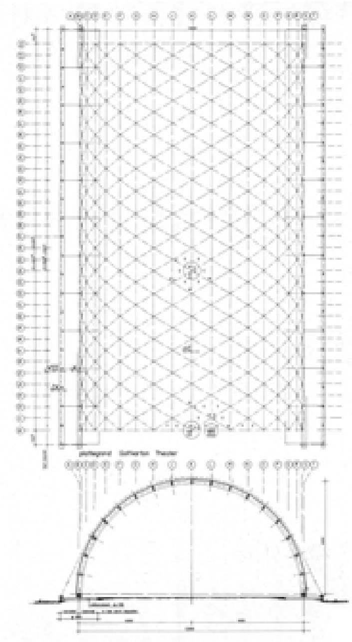

FIGURE 4.24 Plan and section of Apeldoorn Cardboard Theatre, 1992

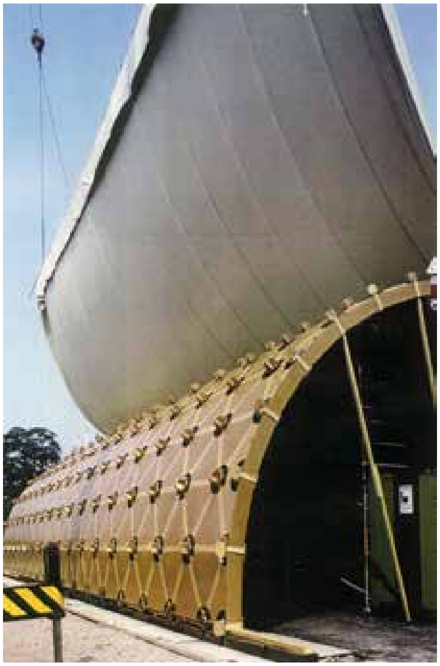

FIGURE 4.25 Watertight membrane covering the cardboard structure with a separate canvas membrane from the top downwards , 1992

FIGURE 4.26 Connection between cardboard member, 1992

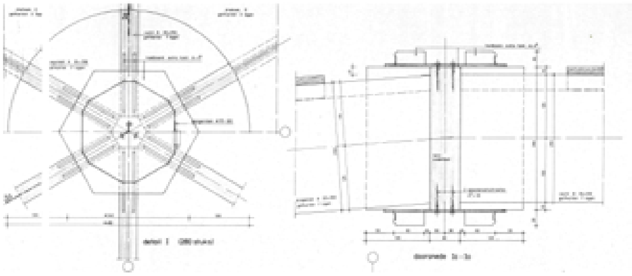

FIGURE 4.27 Details of connections between members

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FIGURE 4.28 View of the inside of the theatre, 1992

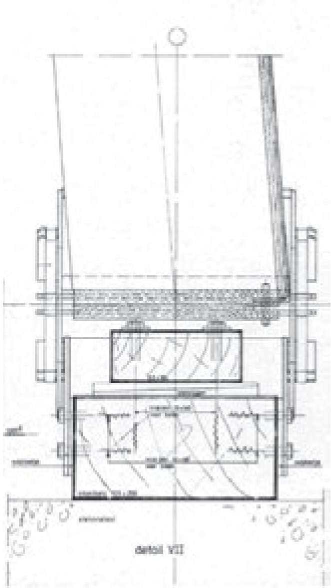

FIGURE 4.29 Detail showing how the members were connected to the ground, 1992

§ 4.3.3 Paper House

Authors: Shigeru Ban Architects
Year: October 1990 to July 1994; construction: October 1994 to July 1995
Location: Lake Yamanaka, Yamanashi, Japan
Area: 100m^2 (size L)
Lifespan: Permanent
Type: Housing

The architect's own summer house is the first permanent construction ever in which paper tubes were allowed to be used as a structural material. The Paper House is composed of 110 paper tubes, which by an S-shape arrangement divide the living space, circulation area, bathroom and small garden (see Fig. 4.3). The boundaries of the house are demarcated by a 10x10m^2 large roof area and enclosed by sliding glazed panels which are a reference to traditional shoji panels. The circular living area lacks furniture, except a kitchen counter and movable closets (see Fig.4.31). The interior can be divided into separate rooms by sliding walls for a private area and living space. The purity of the building is accentuated by the horizontal lines of the roof and the floor,

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and the vertical lines of the paper tubes (see Figs. 4.30 and 4.33). In the gallery circling the living space, a paper tube (1,270mm in diameter) functions as a toilet and a single tube (280mm in diameter) marks the entrance to the house. A smaller circle consisting of 29 externally placed tubes comprises the bathroom and the garden. A total of eighty paper tubes with an external diameter of 280mm (15mm thick and 2,700mm long) are placed inside the building. Ten of the tubes carry the vertical forces from the roof and 80 tubes carry the lateral stress on the structure caused by wind and earthquakes. Although the forces are different in the vertical and lateral directions, all the paper tubes are the same size in order to preserve the purity and elegance of design. Each of the tubes is connected, as they are cantilevered from the floor, to timber cross-shaped connection by means of twelve lag screws. Timber connectors are anchored to the foundation. In October and November 1991, prior tests on paper tubes were conducted at Waseda University in Tokyo. The short-term strength of the paper tubes was tested to determine whether they could withstand bending and axial compression and whether they were strong enough for a wood-to-paper connection by log screw. As humidity also plays an important role with this kind of material, the moisture content was also measured. The average moisture content of the material was 8.8 percent. Tests showed that bending strength was 161.3 kg/cm^2 and compression 113.9 kg/cm^2. In 2013, during a conversation at Kyoto University of Art and Design, Shigeru Ban informed Jerzy Latka that the Paper House built eighteen years previously was still standing and that the paper tubes were in good condition. However, the building was barely used as Ban lived either out of a suitcase or in Paris, and some elements of the structure, such as the concrete feet, had cracked with time. [1, 14, 16]

FIGURE 4.30 Paper House, 1995

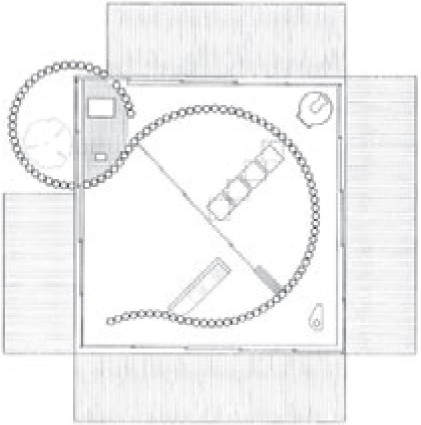

FIGURE 4.31 Floor plan of Paper House, 1995

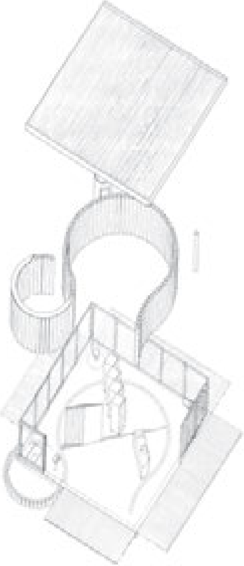

FIGURE 4.32 Exploded axonometric view of the structure of Paper House, 1995

FIGURE 4.33 iew from the inside of Paper House, 1995

§ 4.3.4 Paper Log House

Authors: Shigeru Ban, VAN
Year / Location: August 1995, Kobe, Japan; January 2000, Kaynasli, Turkey; September 2001, Bhuj, Gujarat, India; 2014, Daanbantayan, Cebu, the Philippines
Area: 16m^2 (size M)
Lifespan: Temporary
Type: Emergency shelter

In the year of 1995 Shigeru Ban started the Voluntary Architects' Network, a non-governmental foundation whose aim is to build aid facilities for the victims of natural disasters or disasters caused by human activity. The VAN Foundation's activities focus on research and the design and erection of emergency buildings. The volunteers engaged in the organisation are mostly students of Shigeru Ban's, as well as students and architecture professionals who come from different parts of the world to participate in the projects. [19]

The first emergency building constructed by Ban and VAN was Paper Log House. It was designed for the Vietnamese community living in Japan that lost their homes during the Great Hanshin-Awaji Earthquake in Kobe in 1995. Paper Log House (see Fig. 4.34) has a ground floor area of 6x6m. Its structure was made of paper tubes with a diameter of 108mm and a thickness of 4mm, placed next to each other and connected to each other with self-adhesive sponge tape. For additional support, steel rods were placed horizontally into the cardboard tubes. The walls were attached to the floor boards by means of wooden pegs. The base board was set on foundations made of beer crates and filled with sand bags (see Fig.4.38). The roof was covered with a PVC membrane stretched on a frame made of paper tubes. The roof's gables could be opened during the summer to get an air flow (see Figs.4.36 and 4.37). The construction of the Paper Log House was simple and could be managed by non-professionals. After the house had been erected, the paper tubes were painted with a polyurethane-based varnish. The cost of one unit built in Kobe was approximately USD 2,000 and it took a group of two to four volunteers six hours to erect it. Twenty-seven Paper Log Houses were built in Kobe in 1995. The shelters were also put up in other parts of the world. Seventeen units were constructed in Turkey in 2000, twenty units in India in 2001 and a few units in Daanbantayan in the Philippines in 2014. Both the Turkish and Indian solutions differed slightly from the original Kobe houses. Because Turkish families tend to be larger, the Turkish Log Houses were 3x6m. In Turkey the paper tubes were filled with waste paper for improved thermal insulation. Lack of beer crates in India resulted in the foundations being built out of rubble left over from destroyed buildings, covered with a layer of soil flooring. The roof vaults in India were made out of cane mats with a tarpaulin placed on bamboo ribs. The veranda added to the house offered a shaded outer space (see Fig. 4.35). The most recent version of the Paper Log House was built in 2014 in the city of Daanbantayan, the Philippines. This time round, paper tubes served only as a frame structure covered with locally produced bamboo-mat walls, which allow air and light to pass through. The Philippines project was based on the idea of Paper Partition System No. 3, i.e., lightweight partitions as developed by Ban in 2006. The Paper Log Houses, built from recyclable and locally sourced materials, minimalised the problems of waste left over after usage. [1, 14, 19, 20]

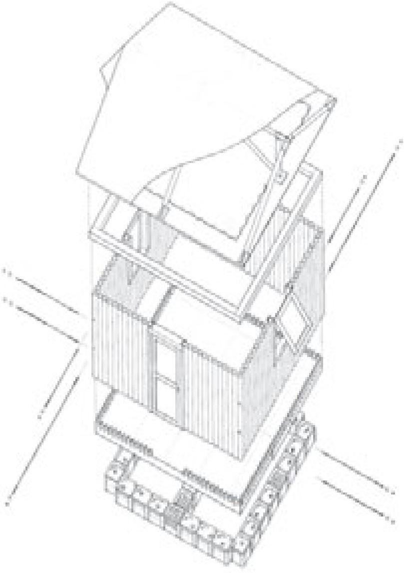

FIGURE 4.34 Paper Log House in Kobe, Japan – exploded axonometric view, 1995

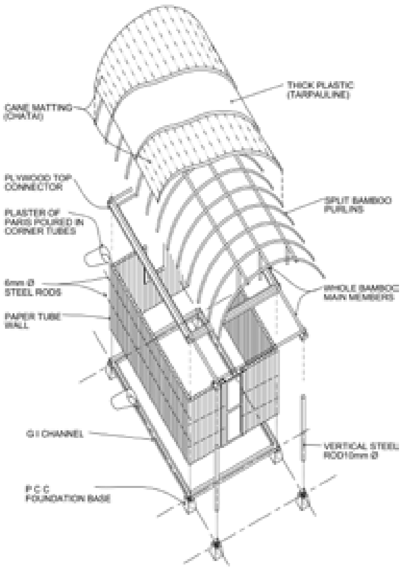

FIGURE 4.35 Paper Log House in Bhuj, India – exploded axonometric view, 2001

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FIGURE 4.36 Paper Log House at an exhibition in Mito, Japan, 2013

FIGURE 4.37 Paper Log House at an exhibition in Mito, Japan, view from the inside, 2013

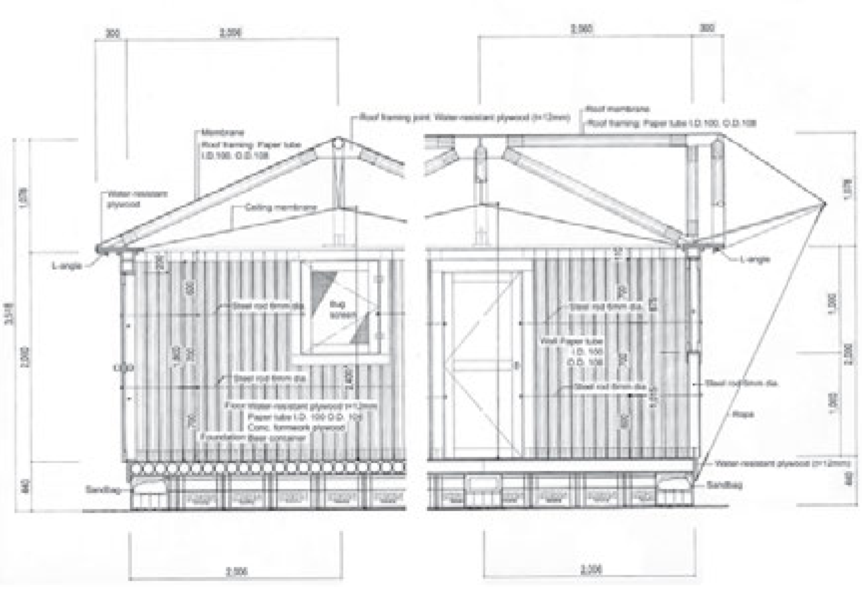

FIGURE 4.38 Paper Log House in Kobe, Japan – detailed section, 1995

In the same year in which the Paper Log Houses were built in Kobe, Shigeru Ban, in association with 160 volunteers from all over Japan, built the Takatori Paper Church for the Vietnamese community. The outer skin of the church was installed on a rectangular area of 10x15m and enclosed by polycarbonate sheeting. The interior of the church, whose elliptical plan made reference to Italy's seventeenth-century Bernini-designed churches, was created out of 58 paper tubes, 330mm in diameter. The walls were 15mm thick and 5m high. The roof of the church was made of tent material. After ten years the Paper Church was dismantled in June 2005 and rebuilt in Taiwan in 2008 (see Fig. 4.39). [16]

FIGURE 4.39 Paper Church in Kobe, Japan, 1995

§ 4.3.5 Paper Arch Dome

Authors: Shigeru Ban Architects, Van Structural Design Studio
Year: 1998
Location: Masuda, Gifu, Japan
Area: 445m^2 (size: L)
Lifespan: Permanent
Type: Workshop

This arch structure was built as an extension to an open-air wood-working place, to be used particularly during the winter. The structure covers an area of 22.8x27.8m^2 (see Fig. 4.40). The aim of the project was to create a simple structure, possibly to be built by a team of carpenters rather than professional construction workers. The structure of a single arch consists of eighteen 1.8m long paper tubes with an internal diameter of 250mm and walls 20mm thick (see Fig. 4.41). The tubes were connected through laminated timber joints by means of lag screws (see Fig.4.44). Timber joints formed the shape of the arch, while the paper tubes remained straight. The top height of the arch is 8m. Nineteen arcs were interconnected by horizontally placed paper tubes with a length of 0.9m, internal diameter of 130mm and walls 5mm thick. For lateral stiffness, the paper tube arcs were covered with structural plywood. Each panel contains a hole with a 500mm diameter to allow natural light to enter. Translucent corrugated polycarbonate panels were placed on top of the plywood (see Fig. 4.45). Additional steel rod bracing was used for stability to allow for sudden load changes, caused, for example, by great amounts of snow falling from the roof.

The whole structure was fixed on concrete foundations that began the curvature of the arch. On the bottom part of the arch extra paper tubes were installed in order to stiffen the structure and to take the bending moments from the connection with foundations (see Figs. 4.42 and 4.43). As the structure was subject to changing weather conditions, the paper tubes were covered in advance by pure polyethylene for protection against humidity. In spite of the fact that paper tubes had been accepted as a building material for the Paper House project, Shigeru Ban had to conduct more tests to prove the stability of the structure.

The test conducted to assess the compression and bending strength of paper tubes showed that compressive strength decreased in an inverse ratio to the rise in moisture content. Ninety-five specimens of paper tubes with an outer diameter of 95mm and walls 5mm thick and a length of 259mm were tested under different moisture conditions. Up to the 7% moisture content level, the paper tubes retained their compressive strength. Then between 7% and 13% their strength gradually decreased, and once the moisture level exceeded 13%, the strength of the tubes was clearly compromised. [1, 16]

The tests confirmed the beneficial collaboration of paper and wood when the two materials were connected. [14]

The idea of Paper Dome structures was later employed in other Shigeru Ban projects: Paper Studio at Keio University (2003), Paper Temporary Studio on the sixth floor roof terrace of the Centre Pompidou in Paris (2004), and Shigeru Ban Studio at Kyoto University of Art and Design (2013).

FIGURE 4.40 Paper Dome, 1998

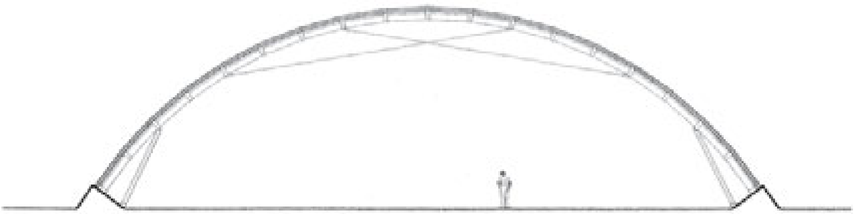

FIGURE 4.41 Paper Dome – section, 1998

FIGURE 4.42 Paper Dome – connection with the foundation, 1998

FIGURE 4.43 Paper Dome –connection between paper tubes, 1998

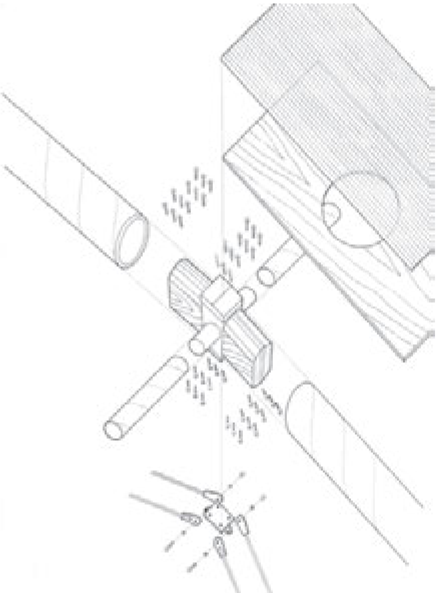

FIGURE 4.44 Paper Dome – detail of the connection between the paper tubes and timber joints, 1998

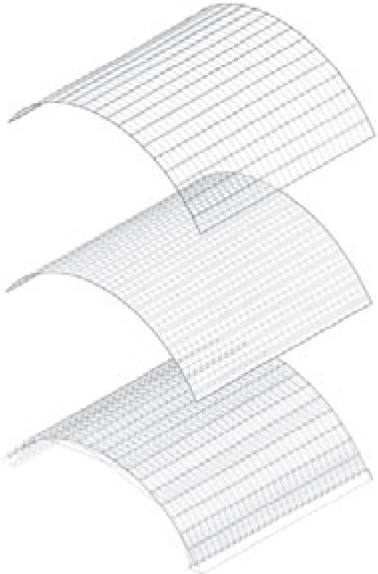

FIGURE 4.45 Paper Dome – layers of the structure, 1998

§ 4.3.6 Nemunoki Children's Art Museum

Authors: Shigeru Ban Architects
Year: 1999
Location: Kakegawa, Shizuoka, Japan
Area: 320.2m^2 (size: L)
Lifespan: Permanent
Type: Public building

FIGURE 4.46 Nemunoki Children's Art Museum, 1999

In his project Nemunoki Children's Art Museum, realised in Kakegawa, Japan, in 1999, Shigeru Ban applied the lattice made of panels with a honeycomb structure as a lightweight stiffening and strengthening element of the roof construction (see Fig. 4.46). The lattice structure is similar to the one used as the gable walls in the Japanese Pavilion in Hannover. Honeycomb panels used as a roof structure were covered with translucent PVC and also served as caissons to prevent direct sunlight from penetrating from above (see Fig. 4.50). The product used in the construction of the museum was not a typical honeycomb panel, which is created by gluing the top and bottom surface with the honeycomb grid in between. The grid-core panels used in the Museum were composed of two moulded sub-panels opened from one side. Two sub-panels were then glued together, creating much stronger material. The structure of the roof lattice was based on an equilateral triangle, with walls 3,000mm long and 600mm high (see Fig. 4.47). This basic unit was stiffened by a 1,000mm triangular division inside.

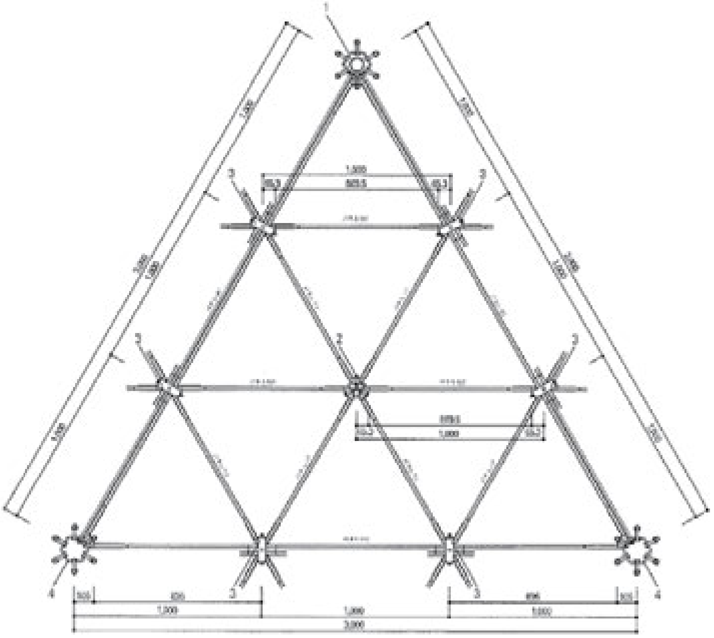

FIGURE 4.47 Nemunoki Children's Art Museum – grid-core cardboard lattice scheme, 1999

The honeycomb panels were connected by aluminium plates to form 60° triangles. The plywood boards were placed inside the honeycomb panels to reinforce the bolt connection with aluminium plates (see Figs. 4.51 – 4.55).

The roof lattice with triangular pattern was connected by four types of aluminium joints:

- The joints that connect six boards to a hexagonal die-cast pipe that was connected with the pillar.
- The joints that connect the 3,000x600mm honeycomb grid-core panels from two directions.
- The joints that attach six 1,000x600mm honeycomb panels to a triangular die-cast pipe with a 60° angle between.
- The joints that connect six boards to a hexagonal die-cast pipe.

The whole structure of the roof was composed of 64 triangular basic units whose walls were 3,000mm long. The use of a roof structure based on a triangular grid allowed the architect to use limited types of connections and to create a lightweight and rigid planar structure. Fully glazed walls and translucent PVC covers over the roof protect the grid-core panels from the impact of the weather (see Figs. 4.48 and 4.49). The climate-controlled interior of the Nemunoki Museum assumed an interior temperature of 20°C and relative humidity of 60%. In September and October 1998 a series of tests on grid-core panels was conducted. The panels were tested for tension, compression, bending moments and adhesion strength between plywood and grid-core panel skins. The tests were carried out at different levels of humidity (60% and 90%). Tests showed that the grid-core panels had a 9.5% moisture content at a relative humidity level of 60%, and a moisture content level of 15.8% at a relative humidity of 90%. At the same time, the compression strength of the panel with a moisture content of 15.8% dropped to 61% compared with the compression strength of the panel with a water content of 9.5%.

Honeycomb panels are more resistant to the equally distributed forces perpendicular to the plane. Thus a combination of corrugated boards with corrugation in the vertical direction and honeycomb panels could increase stiffness in both the vertical and lateral directions.

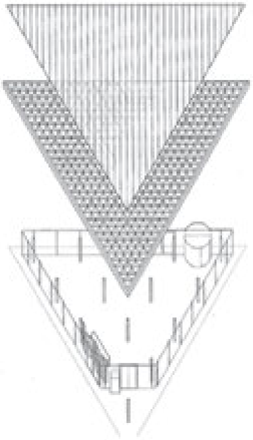

FIGURE 4.48 Nemunoki Children's Art Museum – exploded axonometric view, 1999

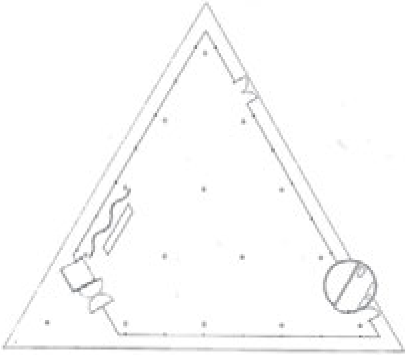

FIGURE 4.49 Nemunoki Children's Art Museum – plan view, 1999

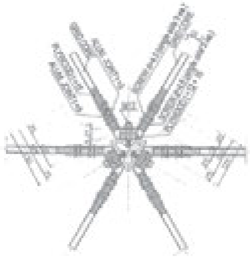

FIGURE 4.50 Nemunoki Children’s Art Museum – detail of the roof structure, 1999

FIGURE 4.51 Nemunoki Children’s Art Museum – aluminium connectors, 1999

FIGURE 4.52 Nemunoki Children’s Art Museum – aluminium connectors, 1999

FIGURE 4.53 Nemunoki Children’s Art Museum roof structure and construction, 1999

FIGURE 4.54 Nemunoki Children’s Art Museum, construction of the roof, 1999

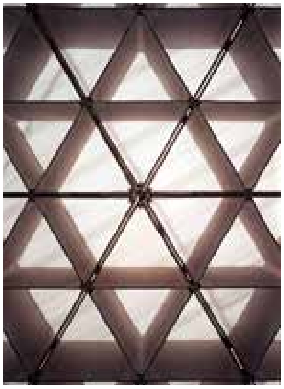

FIGURE 4.55 Nemunoki Children’s Art Museum, grid-core cardboard lattice roof, 1999

The honeycomb structure used in the Nemunoki Children’s Art Museum was authorised by Japan’s Minister for Construction and has been approved for use in Germany, as well.

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§ 4.3.7 Japan Pavilion, World Expo 2000, Hannover

Authors: Shigeru Ban Architects
Consultant: Prof. Frei Otto; Structural engineer: BuroHappold; General contractor: Takenaka Europe GmBH
Year: 2000
Location: Hannover, Germany
Area: 3,090m^2 (size: XL)
Lifespan: Five months
Type: Temporary event venue

FIGURE 4.56 Japanese Pavilion for Expo 2000 in Hannover

The idea behind the design for the Japan Pavilion at Expo 2000, held in Hannover, was to build the structure from recyclable materials to the maximum extent possible, in response to the theme of the Expo: 'Humankind - Nature - Technology: A New World Arising'. Also, ideally it should only barely touch the ground, so as to reduce the footprint left following the demolition of the pavilion.

FIGURE 4.57 The interior of the Japanese Pavilion at Expo 2000 in Hannover

The building, which measured 74x25m and was 16m high, was constructed in the form of a three-dimensional grid shell with indentations along the length of the structure (see Fig. 4.56). The tension between paper tubes obtained by raising the flat structure turned the tubes in a gentle and curvilinear manner that provided sufficient strain to support the structure. The double curved one-metre grid shell was composed of 440 continuous cardboard tubes whose diameter was 120mm and whose walls were 22mm thick, covered with acrylic varnish (see Fig. 4.57). The size of the tubes was determined by the curvature of the whole structure. One hundred and twenty millimetres was the maximum diameter that allowed tubes to be bent to a required 10m radius of curvature. The project involved the use of paper tubes created to 'infinite' length by means of spiral winding. The tubes were fabricated to a twenty-metre length for transport, then connected to wooden inserts. The paper tubes set on the one-metre diagonal grid were connected with fabric tape to allow three-dimensional movement and rotation of the tubes during the erecting process. Due to the risk of paper tube creep over time, the structure was strengthened with arcs in the form of laminated timber ladders with rafters running longitudinally along the structure. The ladders were composed of doubled 60x75mm timber members with some distance in between. A continuous horizontal purlin measuring 60x95mm was fixed between the members of the ladders (see Fig. 4.59). Laminated timber laths created a grid of approximately 3x3m. Additionally, 8mm thick stainless steel cable bracing was fixed to the timber ladders with steel straps. The arc ladders facilitated covering of the external surface of the building. The inner membrane was composed of five layers of flameproof polyethylene, non-combustible paper and a glass-fibre fabric in the middle. The outer membrane was made of transparent polyester fabric coated with PVC (see Fig.4.58).

FIGURE 4.58 Exploded axonometric view of the Japan Pavilion, 2000

FIGURE 4.59 Detail of the connections between the paper tube lattice and timber ladder, 2000

FIGURE 4.60 Detail of a gable wall, 2000

The semi-circular gable walls were bookended by two timber arches clamped to the ends of the paper tube grid shell. The gable walls were composed of triangular panels made from plywood, honeycomb cardboard panels and paper membrane (see Fig. 4.60). They were constructed like a tennis racket, with cables at a 60-degree angle from the foundation. The foundations of the building were made of A-shaped steel frames located under each of the arc ladders. The frames were fitted with timber boards and filled with sand. At the foundations and at the end of the arches paper tubes were joined with screws. The structure was erected by elevating the flat grid previously placed on the Peri scaffolding system.

The tubes produced by Sonoco were tested at Dortmund University in order to get more information about the long-term structural performance of the material. The chosen safety factor was similar to EC5 for timber structures, i.e., safety factor $\gamma = 4$.

Tests were conducted to assess short- and long-term axial compression and short- and long-term bending moments. Furthermore, an axial compression test was performed after the assembly simulation to check if the paper tubes would lose their strength following adjustment of their curvature. Following the assembly simulation test,

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specimens with a length of 1,000mm were cut and tested for respective compression strength. No irreversible loss in the strength of the material was detected in the test. In order to check the impregnation with acrylic paint, the paper tubes were tested for compression after being exposed to a weathering cycle. Five specimens were subjected to a seven-day test following the following procedure: on Days 1-5, specimens were subjected for three hours to a temperature of 70°C and 15% humidity, and to rainfall for one hour. On Days 6 and 7, specimens were subjected for two hours to a temperature of 15°C, 15% humidity and a frost-defrost cycle without any rainfall at temperatures of -20°C and +50°C. After a week's exposure, the specimens were tested for compression and bending. The tests showed that neither the bending nor the compression strength of the specimens changed, compared to fresh specimens.

At the Institute for Building Materials, Concrete Structures and Fire Protection, the paper membrane provided by TSP Taiyo was tested for fire protection performance. The paper membrane, which was composed of flameproof polyethylene film, a non-combustible 'OK Cosmo' paper layer, glass-fibre fabric, a non-combustible 'OK Cosmo' paper layer and flameproof polyethylene film, was conditioned to standard atmosphere for two weeks. Five specimens were exposed to flames for fifteen seconds. The tests showed that the examined material should be designated as standard inflammable Class B2. Although the provided incombustible paper passed the tests, due to the possibility that the Pavilion might become a target for a terrorist attack, an additional layer of PVC membrane meeting the Class B1 incombustibility standards was required. Unfortunately, the Japan Pavilion was demolished after use, instead of being recycled. [1, 14, 16]

The Japan Pavilion was a milestone in paper architecture. All the structures realised in Hannover had to fulfil the strict requirements of the German Building Code, even if they were only used for five months. As the structural engineers from BuroHappold concluded in their publication The Japan Pavilion for the Hanover Expo 2000, the Paper Pavilion 'was a stepping stone in the development of paper architecture and has led to further structures being constructed elsewhere in the world'. [21, 22]

§ 4.3.8 Westborough Primary School, UK

Authors: Cottrell & Vermeulen Architecture
Structural engineer: BuroHappold; General contractor: Takenaka Europe GmBH
Year: 2001
Location: Westcliff-on-Sea, Great Britain
Area: 90m^2 (size: M)
Lifespan: Semi-permanent (twenty-year lifespan)
Type: Public building

Westborough Primary School was the first permanent paper structure built in Europe. The building was an experimental design by Cottrell & Vermeulen Architecture in cooperation with Buro Happold Engineering. A social room for children was built in 2001 and is still in use fifteen years later (as of February 2016).

The building was designed for a twenty-year lifespan and its primary aim was to reduce the environmental impact of building materials by using cardboard (a recyclable material) as a main structural and cladding component. The area of the building is 90m^2 and it serves as an 'after-school club' that has its own open space, toilets and service room (see Fig. 4.61).

FIGURE 4.61 Westborough School, South façade, 2001

The structure of the building consists of two kinds of elements: paper tubes and

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sandwich panels. Two inner walls are composed of eleven paper tubes standing next to each other, which carry the timber truss structure of the roof. Another seven paper tubes were placed in a row, at intervals. These take the loads from the roof, on the side where a big opening for the sliding doors in the northern wall appears (see Fig. 4.62).

The wall and the roof panels are a layered composition of four alternating full cardboard panels 4mm thick each and three honeycomb panels 50mm thick each (see Fig. 4.63). The layers of the panels were fitted into a timber frame and laminated together. The size of the panels was limited by the production process to a maximum height of 2.7m and a width of 1.5m. To minimise the risks posed by moisture and contact with water, the panels were covered with a poly-coated layer on the inside and waterproof building paper on the outside (see Figs. 4.64 and 4.65). Thanks to the vapour barrier on the inside and the breathable water barrier on the outside, the flow of the water vapour into the cardboard was minimised and the vapour was allowed to escape from the cardboard. Full board cardboard protects the inside of the panels. Since cardboard is a relatively fragile material, the final outer layers of the wall and roof panels were additionally covered with 16mm fibreboard-cement panels to prevent them from being damaged by playing students, hail or rain. Eight different types of panels were produced for the folded plate construction forming the wall and roof of Westborough Primary School. [23]

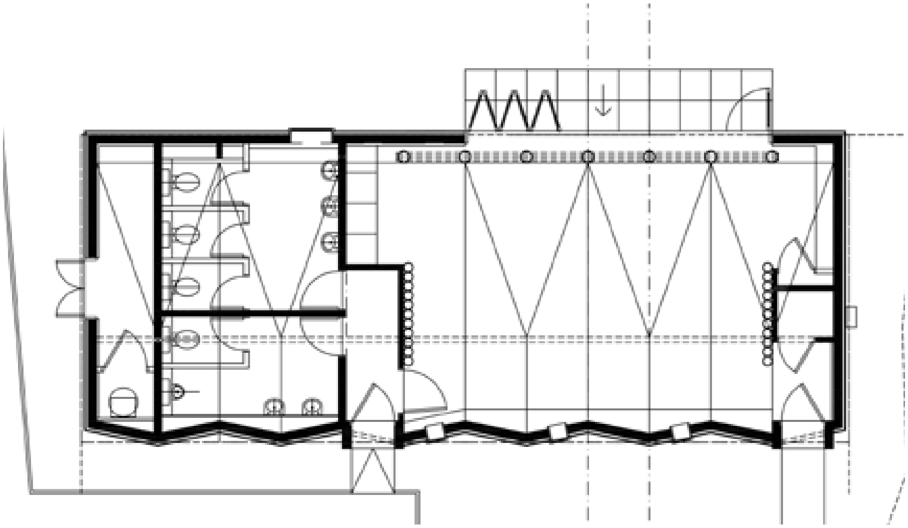

FIGURE 4.62 Westborough School, plan view, 2001

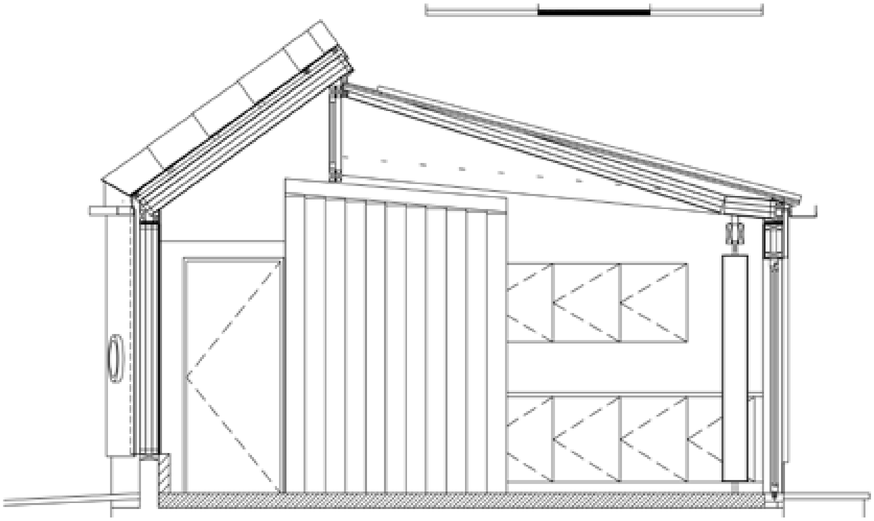

FIGURE 4.63 Westborough School, section, 2001

The joints used between the cardboard elements in both columns and panels were prefabricated wooden elements glued to the cardboard (see Figs. 4.66 and 4.67). The wall and roof panels were simply connected by timber frames which only required a few screws to keep in place. All the exposed surfaces received a fire treatment in order to reduce the risk of damage

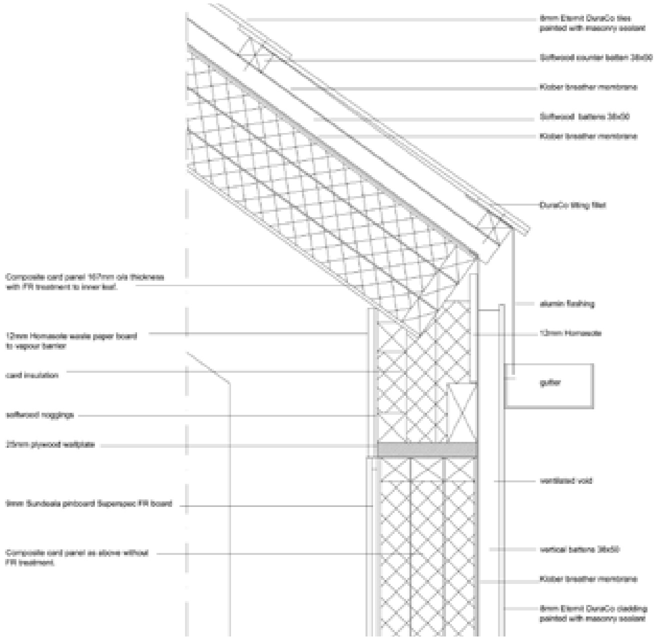

FIGURE 4.64 Westborough School, detail of connection between the wall and the roof panels at the eaves of the building, 2001

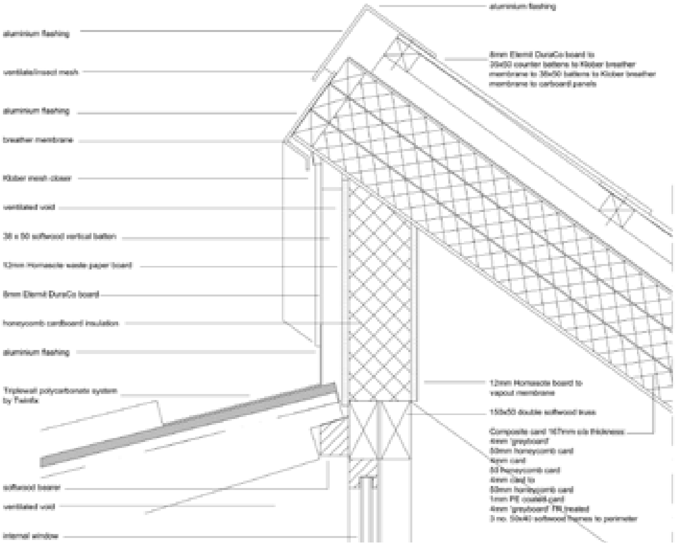

FIGURE 4.65 Westborough School, detail of connection between the wall and the roof panels at the ridge of the building, 2001

FIGURE 4.66 Westborough Primary School, paper tubes structure at the northern side of the building, 2001

FIGURE 4.67 Westborough Primary School, detail of connection between the wall and the roof panels, 2001

The main goals of the project were to prove that cardboard can be used as a full building material, which can be recycled after the lifespan of the building. The assumption was that 90% of the used material would be both recycled and recyclable after use. [23]

Before the final erection of the building, a 6x2.4m^2 prototype was built in order to check buildability and to see how easy it was to connect the building components. During the construction of the prototype, several details of the walls and roof were checked and improved.

BuroHappold conducted a series of tests of water and fire resistance, strength, creep and durability. These tests indicated that a factor of 10% of the compressive strength should be applied in order to avoid the creep of material. They also indicated that structural paper tubes should be protected from moisture and significant changes in temperature, and that a water- and fireproof layer should be applied.

Fire tests carried out for the project showed that 5mm thick untreated full cardboard subjected to a flamethrower charred rather than burned, thus creating a natural fireproof barrier. The tests only just failed the requirements for a Class-1 flame spread.

Four months after the building was erected, some deformations in the paper tubes were detected. The tubes supporting the timber truss were fixed in one position. Lateral movement at the top of the wall was caused by the drying-out of paper tubes, which changed their dimensions. Internal partition walls were installed in order to stiffen the outer walls and no more movement was noticed. Furthermore, a deflection of about 10-15mm was noticed on drying paper tubes.

As A. Cripps mentions in his report, [23] there was ‘other risk [that] included the possibility of not receiving planning permission, building control approval or insurance for the completed building, or that the building might fail at some point during construction or the planned lifetime.’

As the project was a prototype and experiment, the costs of the entire structure were rather high, amounting to £142,042 (€167,610), excluding research and design (which probably added another £80,000). However, the cost can be significantly reduced by serial or even mass production of the elements. Finally, the building showed that the goal of having a building consist of 90% recycled and recyclable material could not be attained. In terms of weight, the concrete foundation made up 85 tonnes out of the total 100-tonne weight of the building. In terms of volume (m^3), cardboard accounted for about 29% of the structure, or 56% if the concrete floor slab was not included. [23]

The paper building of Westborough Primary School was granted a number of awards (2002 RIBA Award, RIBA Stephen Lawrence Prize, 2002 RIBA Journal Sustainability Award, 2002 Civic Trust Awards Commendation).

§ 4.3.9 Demountable Paper Dome (IJburg Theatre), Amsterdam, Utrecht

Authors: Shigeru Ban Architects; associate architects: STUT Architecten; system designers, engineers and general contractor: Octatube
Year: 2003 (Amsterdam); 2004 (Utrecht)
Location: IJburg, Amsterdam; later re-erected in Utrecht, the Netherlands
Area: 485m^2, 26m diameter (size: XL)
Lifespan: Nine years (dismantled in Utrecht in May 2012)
Type: Public building

The Paper Dome was designed by Shigeru Ban for Jeannette van Steen’s mime group. As the client was a mime group, acoustics did not play a role in the design of the building. In the spring of 2003 the dome was erected in the sandy and bare environment of IJburg to stimulate the realisation of this new town. In 2004, the Dome was dismantled and re-built in Leidsche Rijn, near the city of Utrecht. The Paper Dome hosted various social and cultural events for the new town and accommodated 225 seated visitors or 700 standing visitors at a time.

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Prior to the design of the details, the fundamental research and development of the material, which took four months, was conducted by the company Octatube, guided by the Chair of Product Development of TU Delft's Faculty of Architecture and the Built Environment and remotely supported by TU Delft's Cardboard research group, led by Prof. Fons Verheijen. No information was available about any previous projects, so Octatube had to start from scratch.

The research focused on the relation between strength and humidity, elastic modulus, buckling and bending strength. Tests conducted in November-December 2002 and January 2003 showed that paper tubes produced by both spiral and parallel winding were not strong enough for the project. The tested specimens had an external diameter of 150-200mm, and their walls were 15-20mm thick. It was noted that they were highly sensitive to moisture, thus resulting in creeping of the material. After four months' research, the American company Sonoco delivered the right paper tubes, which were made of virgin fibres, unlike the previous ones, which were made of recycled paper. It turned out that the paper tubes made of the new type of paper were 40% stronger than the ones made of recycled paper.

FIGURE 4.68 Paper Dome Theatre – paper tube 10-frequency icosahedron, 2003

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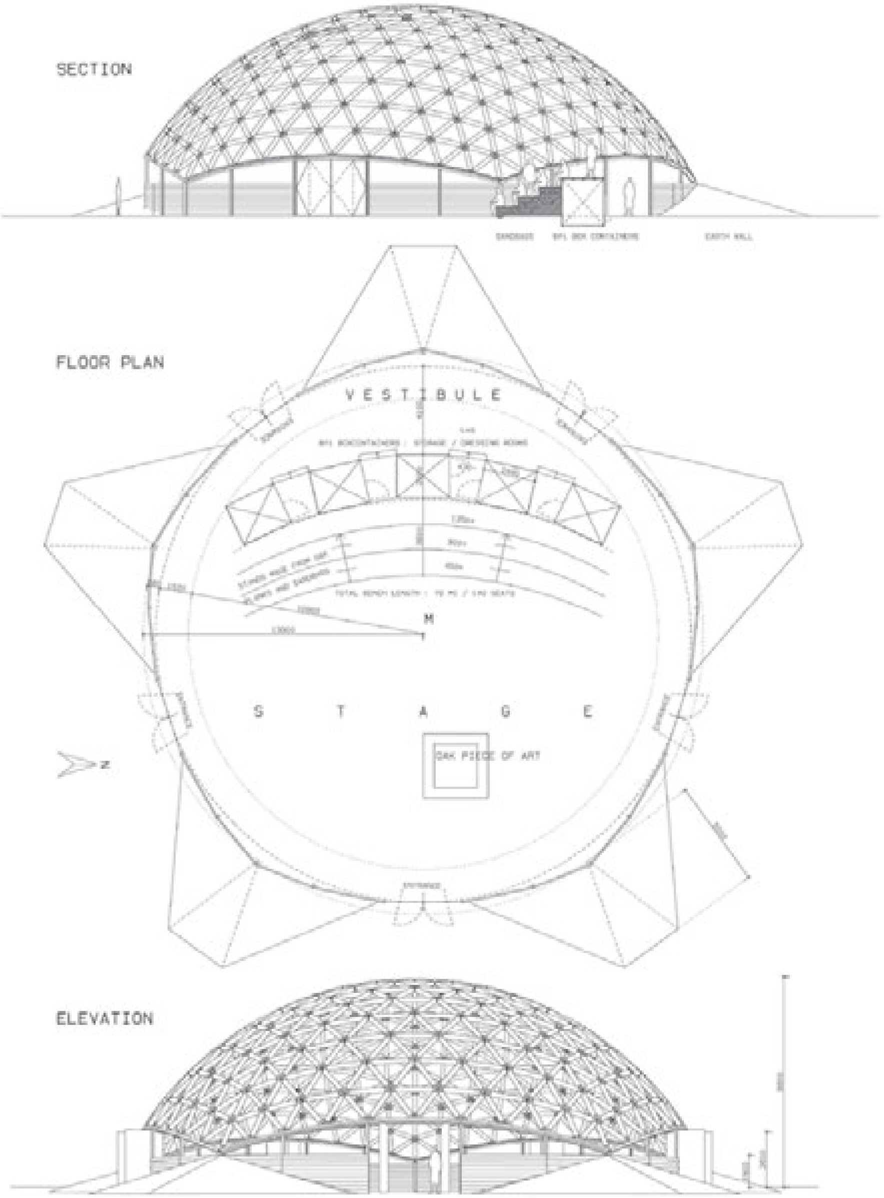

FIGURE 4.69 Paper Dome Theatre – section, floor plan and elevation, 2003

The design conceived by Shigeru Ban was a geodesic 16-frequency icosahedrons dome. However, during the designing process and following discussions with Mick Eekhout, who proposed an 8-frequency dome, Ban changed the design and worked out an idea for a 10-frequency icosahedron dome instead (see Fig. 4.68). This helped increase the length of the paper tubes, produce a smaller number of differently shaped joints and reduce the number of elements used, while preserving the smooth geometry of the dome. The dome had a 26m span and 10m height at the highest point. There were five entrances below curved edge profiles made out of IPE220 steel profiles (see Fig. 4.69).

Five curved edge profiles created the tension ring at the bottom. They were placed on five tetrahedrons to form stable corner columns. The bottom arcs were bolted to the concrete floor slab foundation. As the maximum height of the arcs was 150mm, which would not allow people to enter the dome, it was necessary to dig the ground and lower the entrance level. This problem was solved in the second location (Leidsche Rijn) by placing the foundation elements at the ground level and installing an earth wall all around the building.

The paper tube structure was covered with a PVC-coated polyester fabric membrane. The membrane was attached to small dishes which were placed on threaded rods in the centre of the connection nodes (see Fig. 4.70). Thanks to this solution, a membrane could be stretched and post-stressed by twisting the threaded ends underneath the fabric and pushing the dishes outwards.

Unlike the Japan Pavilion created for Expo 2000 in Hannover, in which long paper tubes crossed each other, the Paper Dome Theatre had a dome whose geometry was defined by joints. Tests proved that cardboard is weak at the transverse screws and bolts. Therefore, a new type of joint had to be created. As the dome was demountable and scheduled to remain in IJburg for a limited period of time, after which it was meant to be transferred to another location, the connections between the paper tubes and joints had to be demountable, as well.

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FIGURE 4.70 Paper Dome Theatre – steel joint, 2003

Seventeen different lengths of paper tubes were used for the demountable dome structure. Approximately 700 paper tubes were used with a length ranging from 1,200mm up to 1,500mm. The external diameter of the tubes was 200mm and the walls of the tubes were 20mm thick. The paper tubes were coated with varnish on the outside, on the cutting edges and 100mm inwards to prevent moisture and water from affecting the structure. The paper tubes were held together by means of star-shaped joints made of steel. Each tube was equipped with a steel lid on either end. Both lids were joined by means of a 10mm-threaded steel rod inside the tube. By rotating, the lids compressed the paper tube and converted it into a pre-stressed element (see Fig. 4.71). In the words of Mick Eekhout *this was an essential pre-stressing concept for the cardboard tubes, invented by Luis Weber of Octatube Engineering, which has been used all over the world since then*[24]. This solution meant that no bolt or screw connections were required, and that the compressive strength of the material was used instead. Steel tube collars with an outer diameter of 152mm were welded to the steel lids. They fit into the paper tubes and kept them in position. On the outside of the lids, square steel plates were welded, which were fixed to the star-shaped connector by means of two bolts to acquire a moment stiff node. The steel star-shaped nodes were made of six steel plates welded on a round steel tube.

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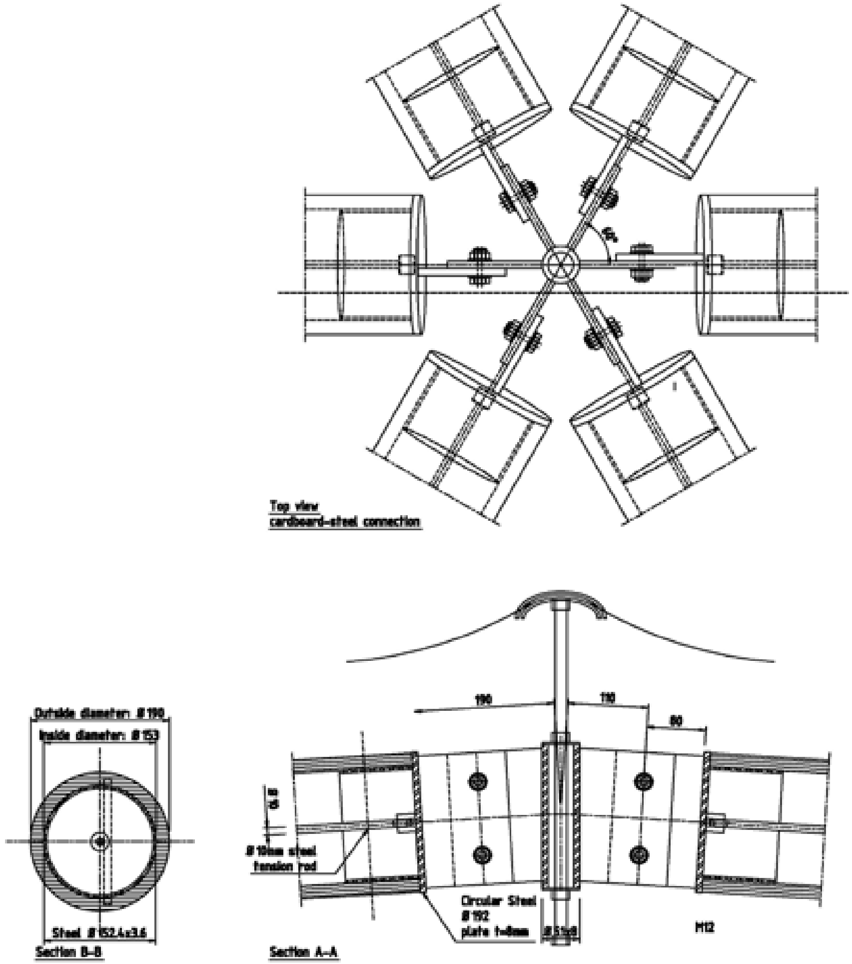

FIGURE 4.71 Nomadic Paper Theatre – steel joint details, 2003

There were eighteen different types of nodes which follow the geometry of the Dome. The types of connections used and the geometry of the Dome resulted in a structure without bending moments in the tubes. All parts of the Nomadic Paper Dome were able to be shipped in four or five shipping containers, which meant the building was truly nomadic. [1, 16, 17, 24]

The Paper Dome has been erected twice and disassembled twice. As of 2017, it is awaiting a new application. For the time being, its components are stored in containers in Amsterdam. Mick Eekhout regrets that due to the short lead-in time of two months for initial engineering and production, no time was available to develop cardboard nodes or composite nodes. He hopes to do so in the future.

§ 4.3.10 Cardboard House, Sydney, Australia

Authors: Peter Stutchbury and Richard Smith, Ian Buchan Fell Housing Research Unit of Sydney University
Year: 2004
Location: Sydney, Australia
Area: 32.4m^2 + 7.9m^2 mezzanine (size: M)
Lifespan: 1.5 years
Type: Housing

In 2004, Australian architects Peter Stutchbury and Richard Smith, in cooperation with the University of Sydney, designed and built the Cardboard House. The project was a part of the Houses of the Future exhibition. Six architectural teams were asked to design a proposition for future housing concepts with ambitious and physical experiments. The houses designed had to be portable and consist of one single material. Six concepts were presented, each made of a different material (concrete, cardboard, glass, clay, steel and timber). Cardboard House was shown to be a low-energy, lightweight, easy-to-transport-and-erect and recyclable solution. As the architects wrote in their submission to the Centre for Affordable Housing, 'The cardboard house represents the reduction of technology, the simplification of needs and the integration of common sense to make a building that may realistically consider a proposal for future living.' [25]

The authors' idea was to create a temporary structure, 85% of which consisted of recycled materials, which could be fully recycled into cardboard after its period of use (see Figs. 4.72 and 4.73).

The building consists of cardboard A-shaped portal frames interlocking with horizontal cardboard spacing beams (see Fig. 4.75). Six portals create five spans of 1.8m each. Simple interlocking pieces result in a rigid and low-technology structure. The house can be expanded in both width and length.

The open space contains service pods like a kitchen and bathroom, with a sleeping mezzanine upstairs, as well as a living-room section on one side (see Fig. 4.74). On the opposite side of the service pods there are pivot door panels, which allow for expanded liveable space. The open space allows cross ventilation and flexible adjustments for the seasonal cycles. Energy is provided by the photovoltaic panels that generate 12 V power.

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FIGURE 4.72 Cardboard House, Sydney, Australia, A-frame cardboard structure, 2004

FIGURE 4.73 Cardboard House, Sydney, Australia, connections between the structural elements, 2004

FIGURE 4.74 Cardboard House, Sydney, Australia, floor plan, 2004

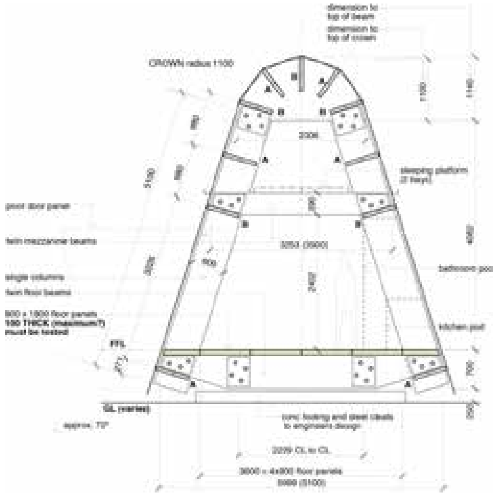

FIGURE 4.75 Cardboard House, Sydney, Australia, section, 2004

The material used in the project was 60mm laminated fibreboard (full cardboard).

Each of the A-shaped frames was composed of two 5,100x600x60mm beams and a semi-circular crown. Nine horizontal spacers (10,200x600x60mm) were interlocked in each of the frames (see Fig. 4.76). The minimised number of fixings between the elements was achieved by interlocking parts of the structure. Elements were held together by 10mm thick cardboard locking plates, 50mm PET tubes and M12 nylon threaded rods.

The outer skin of the Cardboard House was made of HDPE, which also allowed the inhabitants to store grey water in tanks under the floor.

The whole structure was able to be transported by a light commercial vehicle as a flat package, weighing in at 2,000 kg. Most of the members had the following dimensions: 5,000x600x60mm. The Cardboard House was assembled by a group of people who did use scaffolding, but no special equipment. The cost of one kit was approximately AUS$35,000, which equalled €21,500 in 2005. The structure was exposed for approximately a year and a half at three exhibitions held in 2004 and 2005.

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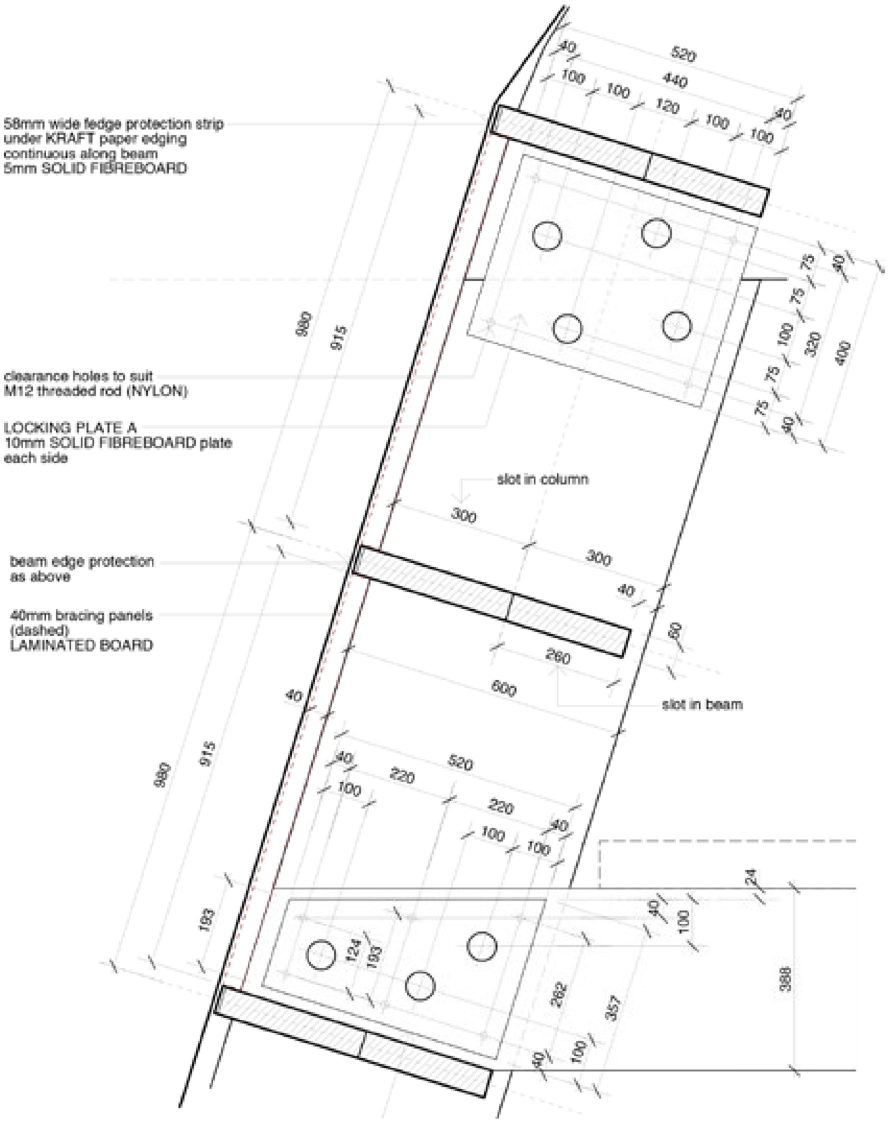

FIGURE 4.76 Cardboard House – detail of the connection between the A-frame and the horizontal spacers, 2004

§ 4.3.11 Hualin Primary School

Authors: Shigeru Ban Architects, Voluntary Architects Network, students of Shigeru Ban Lab and Hironori Matsubara Lab at Keio University, Chengdu Southwest Jiaotong University
Year: 2008
Location: Chengdu, Sichuan Province, China
Area: 3x174m^2 (size: L)
Lifespan: Semi-permanent (estimated five-year lifespan)
Type: Public building/ Emergency

After the major earthquake that shook Chengdu, the capital of Sichuan province, on the 12th of May 2008, Shigeru Ban contacted Professor Hironori Matsubara, who taught at the same university as Ban (Keio University in Tokyo) and also worked as a building consultant in Beijing. A month later, Shigeru Ban, together with volunteers from Ban Lab at Keio University and Chengdu Southwest Jiaotong University, presented a prototype for a house for the victims of the earthquake. At the same time, the Chinese government embarked on a programme designed to build temporary houses for those who had lost their homes due to the earthquake. Although Shigeru Ban was not commissioned to build these houses, he acceded to the request made by the local Rebirth of the Environment NGO and Chengdu Chenghua Primary School that he design and build a temporary Primary school in Chengdu's Hualin district.

Shigeru Ban prepared a proposal for three oblong buildings, each of which contained three classrooms, 9.7x6m per classroom as desired. One of the classrooms was divided into two rooms to provide space for the administrative staff and educators. Each pavilion had an area of 29x6 metres, plus a covered corridor that was 1.5 metres wide (see Fig. 4.77).

The Education Bureau requested that construction be completed by September, to allow students to go to school when the new semester started. While the new school was being designed, the existing and damaged classrooms were demolished. The foundations of the destroyed school were retained and used as the foundations for the newly to be built construction.

The buildings were constructed by students of Tokyo's Keio University and Chengdu's Southwest Jiaotong University as well as volunteer teachers of the school. One hundred and twenty volunteers were divided into three teams, and in order to ensure that the structure was completed before the start of the new school year, a competition was announced for the best and fastest team. All three structures were built in forty days.

FIGURE 4.77 Hualin Primary School, Chengdu, China, 2013

The structural system of Hualin Primary School is based on transverse frames built out of paper tubes. Each of the three erected buildings is 6x29 metres and consists of thirteen transverse frames (see Fig. 4.79. Each frame was constructed out of four paper tubes whose dimensions were 240mm (outer diameter) and 18mm (wall thickness), connected longitudinally with another five paper tubes with the same size (see Fig.4.78). The vertical paper tubes that support the walls are 2,200mm high, the diagonal paper tubes for the roof structure are 3,120mm, and the longitudinal paper beams are 2,200mm long. The paper tubes of the transverse frames are connected with wooden box-shaped joints with studs to which paper tubes are attached. The joints were ordered from a local factory. After they arrived, it appeared that they were empty inside. Some additional reagent had to be used to fill the joints and make them strong enough. Each frame is additionally braced with steel rods. The longitudinal connection between the frames and beams is made of two 18mm laminated plywood boards cut into the shape of a ring with protruding plates to which other plywood plates were fastened to create a cross-like connection. The whole structure was stiffened with plywood boards attached to the paper tube rafters.

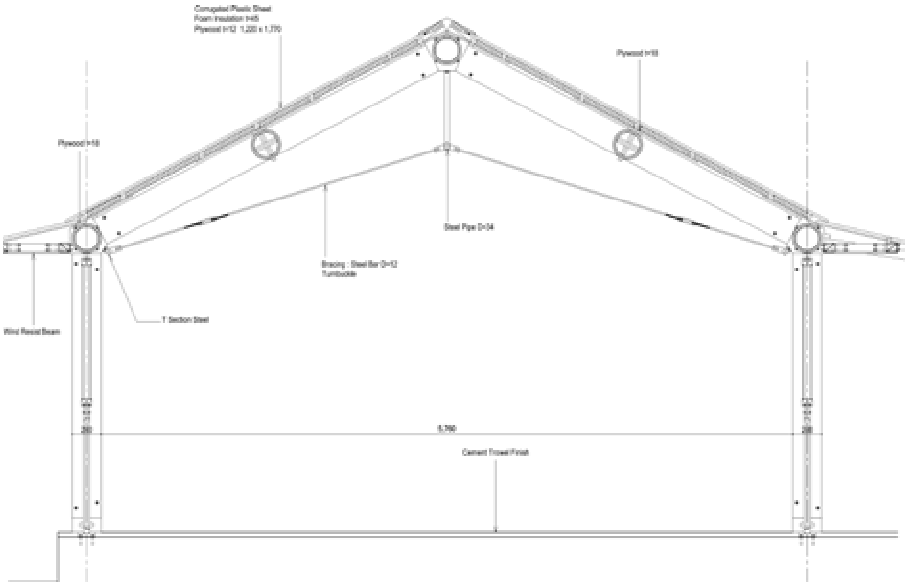

FIGURE 4.78 Section of Hualin Primary School, 2008

The architect's intention was to design a structure which would be easily erected by non-professional construction workers, such as students or volunteers. There are four different types of joints (see Fig. 4.80). The top joints that connect the rafters and columns are designed as wooden blocks with off-standing arms in the shape of octagons to which the paper tubes were attached and fixed in place with 12mm bolts with nuts. The off-standing arms are placed at an angle of 125° for joint A between the rafters and 118° for joint B between the rafter and the column (see Fig. 4.82). The joints for the beams in the middle of the rafter are composed of two 18mm laminated plywood boards. The bottom joint is composed of a rectangular base with an octagonal pin and a T-shaped steel plate at the bottom, which connects the joint to the foundation by means of anchor bolts. The joints were designed in such a way as to facilitate the installation of the frame on the ground and then to connect it with another, previously built frame by raising the whole frame with ropes and manpower. The bolts that fix the paper tubes in position go through the paper tubes and octagonal pins and are tightened from the outside with nuts. Thanks to the octagonal shape of the pins, it was very easy to position the holes for the bolts. The joints are composed of four parts fastened with glue and a steel rod with a diameter of 12mm. They were ordered from the local factory, and as mentioned before, they arrived empty inside. They had to be filled up with an additional extender to ensure they were strong enough.

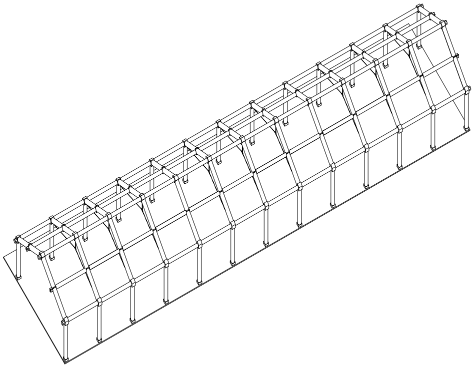

FIGURE 4.79 Axonometric view of Hualin Primary School structure, 2008

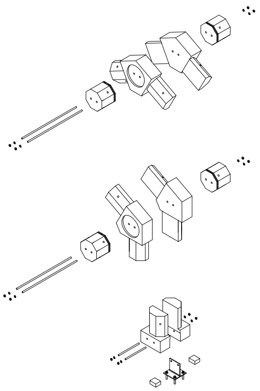

FIGURE 4.80 Hualin Primary School, timber joints types, 2008

The foundations of the previous school building, which was damaged by the earthquake, were re-used for the new Hualin Primary School. The concrete slab was cleaned and prepared during the design process. However, the foundations were too low, and when it rained, water was able to reach the wooden base joint. This resulted in capillary rising damp and its transfer to the paper tubes. The bottom parts of some paper tubes were damaged and had to be replaced with steel tubes as a consequence (see Fig. 4.81).

The walls in the buildings are made out of the PVC sashes with glazing. Panels were fixed to the paper columns through wooden battens screwed to the tubes. Short side walls were built to serve as solid walls, made out of painted white plywood boards with thermal insulation material in between. The wind loads are carried by these solid walls in the cross direction. In the longitudinal direction, wind loads are carried by long paper beams and plywood panels fixed to the paper tube rafters.

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FIGURE 4.81 Hualin Primary School – damaged paper tubes, 2013

FIGURE 4.82 Hualin Primary School – 1:1 scale mock-up, timber joint detail, 2013

Hualin Primary School has a clear and simple roof structure. Diagonal paper tubes serve as rafters. They were rendered harder by five rows of paper tube beams and additionally by steel bracing (see Figs. 4.84 and 4.85). Plywood boards were attached on the top of rafters, which makes the structure stronger in the longitudinal direction. The boards have round cuts in the middle in order to reduce their weight. Insulation foam and corrugated plastic sheets were placed on top of the plywood boards. The roof and eaves of the exterior corridors were constructed using timber beams and plywood. [1, 16, 19, 20, 26]

Hualin Primary School was initially built in 2008 for a five-year period. However, the building was still occupied in 2013, after the end of the estimated lifespan. The school's headmaster told the author there were no immediate plans to abandon or dismantle the building. It is important to keep in mind that in certain situations, like emergency situations, the predicted lifespan of a structure can be significantly extended.

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FIGURE 4.83 Hualin Primary School – roof structure, 2013

FIGURE 4.84 Hualin Primary School – 1:1 scale mock-up, roof structure, 2013

§ 4.3.12 Ring Pass Field Hockey Club

Authors: Nils Eekhout, Octatube
Year: 2010
Location: Delft, the Netherlands
Area: 128m^2 (size: L)
Lifespan: Permanent
Type: Public building

In 2010, Nils-Jan Eekhout of the Dutch company Octatube designed and built a multi-functional extension of the clubhouse of Ring Pass Field Hockey and Tennis Club in Delft. Octatube had previously cooperated with Shigeru Ban on three projects in which paper tubes were used as a construction material: Demountable Paper Dome (2003), Vasarely Pavilion (2006) and Paper Bridge (2007). Each of those projects was a temporary structure. The non-realised cardboard space frames of TU's Faculty of Architecture were one reason to continue the development of a cardboard space frame system, this time designed and executed by the technical director of Octatube. Nils Eekhout's space frame roof structure, consisting of paper tubes, was a permanent one. The space frame consists of paper tubes connected by recycled steel spheres, i.e., Tuball. The structure was prefabricated on the ground in two parts measuring 8x8 metres each and lifted into position. The roof structure is supported by steel columns (see Figs. 4.85 and 4.87).

FIGURE 4.85 Ring Pass Field Hockey Club, social room, 2012

As with the Nomadic Paper Dome, the paper tubes were not connected by screws so as to avoid concentrated forces which could easily damage the cardboard, but rather by pre-stressed steel threads that were placed inside the tubes and were connected to the Tuball. The threads end in nuts inside the openable Tuball. Tightening them means that the paper tubes are subjected only to stress. The flanges of the Tuballs are sealed with rubber in order to prevent the ingress of moisture (see Figs. 4.86, 4.88, 4.89).

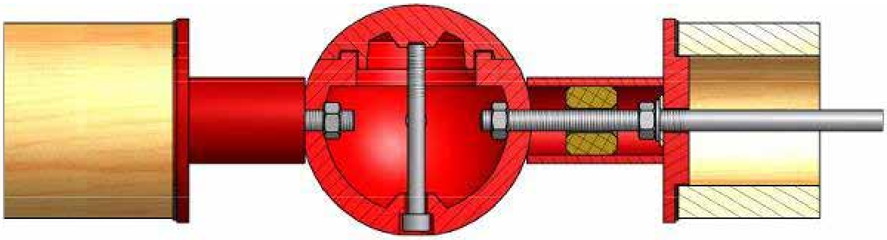

FIGURE 4.86 Ring Pass Field Hockey Club, section drawing of a Tuball, 2010

FIGURE 4.87 Ring Pass Field Hockey Club, social room roof structure, 2012

At the Ring Pass Field Hockey Club, various alternatives were used to protect the paper tubes. The paper tubes are not directly exposed to external weather conditions. The paper tubes were treated against water and moisture in three different ways, which are monitored periodically:

1. Tubes with polyethylene sleeves. The sleeves were applied to the paper tubes, then treated with heat to shrink them. There are two types of sleeves. One covers only paper tubes; the other covers paper tubes and the flanges of the Tuballs;
2. Tubes painted varnished on the inside and outside;
3. Tubes left completely untreated. Humidity does not affect the uncoated paper tubes inside the building.

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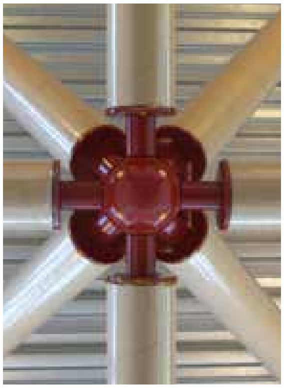

FIGURE 4.88 Ring Pass Field Hockey Club, Tuball – connection between paper tubes, 2012

FIGURE 4.89 Ring Pass Field Hockey Club, Tuball – connection between paper tubes and steel column, 2012

The Ring Pass Hockey Club was authorised to use the paper tube space frame for a permanent structure. It was the first example of a permanent structure made of cardboard in the Netherlands. The building is fully compliant with the requirements for permanent buildings. It is also fully compliant with Dutch fire safety requirements. Contrary to popular belief, cardboard created by high-density material creates a carbon layer when subjected to flames. It takes a long time before this type of cardboard catches fire.

Prior to the Ring Pass Field Hockey Club, Prof. Mick Eekhout designed a cardboard space frame for TU Delft's Faculty of Architecture's Glass Houses. As the project was never realised, a description of it is provided below, rather than in a separate sub-chapter.

Cardboard space frame for TU Delft's Faculty of Architecture's Glass Houses

Authors: Mick Eekhout, Octatube Nederland B.V.
Year: 2008
Location: Delft, the Netherlands
Area:30x50m / 30x30m (size: XL)
Lifespan: Initially estimated to be five years, but later defined as permanent
Type: Public building

This Demountable paper dome, designed in 2002, was based on Octatube's nodal space frame system. In 1984 the Octatube company had developed a more abstract system, with hidden bolts and tubular bars and spherical nodes, known as the Tuball system. It was originally executed in aluminium, but mostly in steel. The biggest span realised was 80x150m for a Boeing 747 maintenance hall in Mumbai. In the original design for the extension to the existing TU Delft main office building, to be used by the Faculty of Architecture, it was decided that two large glazed halls should be added, an east-facing hall (30x30m) and a south-facing hall (30x50m) (see Fig. 4.90).

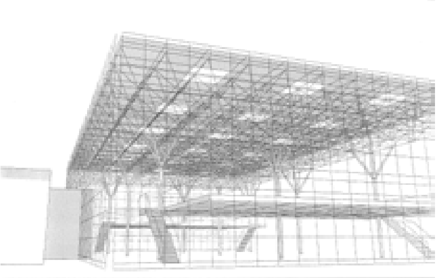

FIGURE 4.90 Axonometric view of the east-facing hall (Orange Hall), 2008

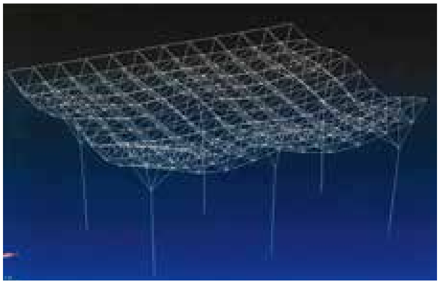

FIGURE 4.91 Static analysis schemed loaded with exaggerated deformations of the card board space frame of the south-facing hall, 2008

In October 2008 a contract was signed stating that both halls would be built using cardboard space frames. As the spans created by cardboard frames are limited in size, it was decided that the spans of the hall would consist of five modules of 1,350m. As a result, both halls have intermediate columns inside the space of the hall. A steel space frame could do it with a free span (see Fig. 4.91). The cardboard mechanical properties were calculated by Octatube on the basis of the data collected in 2002 for the Paper Dome project. The planning of rebuilding after the great fire of the Faculty of Architecture in May 2008 was tremendous and tight. It included three months of experimentation to develop a reliable and certified treatment for the cardboard tubes, so that they would have a long lifetime – twenty to thirty years. One month after the signing of the contract, TU Delft decided that the first hall had to be finished before the start of the 2009-2010 academic year. This meant that by Octatube's three months of experimentation and research had been in vain. Concrete piles, 25m long, had already been driven into the ground, so the underground situation could no longer be changed. The column supports stayed in the same position, and instead of a cardboard space frame, a standard steel Tuball space frame was realised, and the building was scheduled to be completed just in time for the start of the new academic year (see Figs. 4.92 and 4.93). In 2010, Ring Pass hall succeeded the TU Delft cardboard space frame.

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FIGURE 4.92 Realised steel space frame for the south-facing hall Faculty of Architecture TU Delft, 2017

FIGURE 4.93 Space frame structure of the south-facing hall, Faculty of Architecture TU Delft, 2017

§ 4.3.13 Shigeru Ban Studio at Kyoto University of Art and Design

Authors: Shigeru Ban Architects, students of KUAD
Year: 2013
Location: Kyoto, Japan
Area: 142m^2 (size: L)
Lifespan: Temporary
Type: Public building

n 2013 Shigeru Ban became a professor at Kyoto University of Art and Design. To host the students, Ban designed and built a structure similar to the Paper Dome with his students. The arched surface had previously been used as a studio for Ban Lab at Keio University in Fujisawa, Kanagawa Prefecture, in 2003. In addition, it had been used as Shigeru Ban Architects' temporary studio on the sixth-floor roof terrace of Centre Pompidou in Paris in 2004.

The studio covers a usable area of 11.7x12.1m^2. The gable walls were made out of wooden frames covered with PVC-corrugated panels (see Fig.4.94).

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FIGURE 4.94 Shigeru Ban Studio at KUAD, front wall, 2013

Unlike his three previous arch structures, this time Ban used steel joints in order to be able to re-use the structure after its disassembly. The structure of a single arc is composed of six paper tubes with an internal diameter of 170mm. The walls of the tubes are 3.5mm thick and the tubes are 1,860mm long. Twelve arcs are connected with five rows of horizontally placed paper tubes with a length of 850mm and the same diameter (see Fig.4.96). The paper tubes were not connected to the steel joints by means of screws or bolts, as was the case in the previous arc structure. This time, as with the Library of a poet, the Dutch Paper Dome and Ring Pass Hockey Club, the steel threads which were placed inside the tubes tightened the tubes, causing axial compression. Ban now used two tensile rods rather than one (see Fig. 4.95). This called for further development of the end fitting of the cardboard tube.

Transverse tubes were connected and screwed to wooden pegs. The wooden pegs were inserted into the hollow steel connectors of the arches (see Fig. 4.98). Metal joints were connected with bracing in order to keep the structure rigid and to prevent changes in the load distribution due to snowfall (see Fig. 4.97). The surface created by the paper tubes was covered with structural plywood panels. Each of the panels with round openings of 750mm was attached to battens, which were screwed to the paper tubes from above.

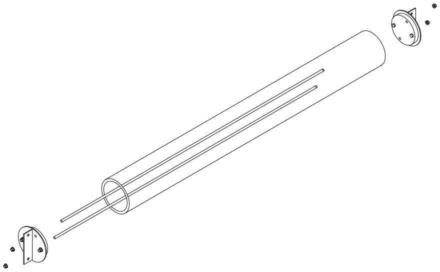

FIGURE 4.95 Shigeru Ban Studio at KUAD, post-stressed connection between paper tube and steel joint with two threads, 2013

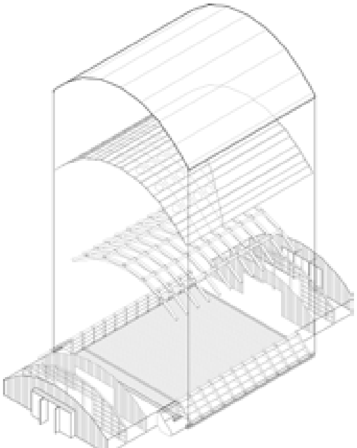

FIGURE 4.96 Shigeru Ban Studio at KUAD, exploded axonometric view, 2013

The structure was placed on top of the concrete slab that covered a big university hall underneath. On the slab, a concrete foot carried 250x250mm steel H beams on either side of the arcs. The corners of the arcs were strengthened by timber boxes that served as shelves.

FIGURE 4.97 Shigeru Ban Studio at KUAD, view from the inside, 2013

FIGURE 4.98 Shigeru Ban Studio at KUAD, detail of a paper-tube connector, 2013

§ 4.3.14 Miao Miao Paper Nursery School

Authors: Shigeru Ban Architects, VAN; structural engineer: Minori Tezuka; construction: students of Shigeru Ban Studio, Kyoto University of Art and Design and Southwest Jiaotong University
Year: 2014
Location: Taiping Town, Ya'an City, Sichuan, China
Area: 117.6m^2 (size: L)
Lifespan: Semi-permanent (estimated lifespan five years)
Type: Public building/ Emergency

On 20 April 2013, a huge earthquake shook China's Sichuan province. It had a magnitude of 7 on the Richter scale. Shigeru Ban, who had built the temporary paper structure of Hualin Primary School in Chengdu after another earthquake in Sichuan five years previously, went to China to see if his structure had survived the earthquake. The Hualin School, built in 2008, had escaped unscathed. During the trip, Shigeru Ban visited the small town of Taiping near Ya'an city. About 70% of the town had been destroyed by the earthquake. Shigeru Ban decided to design and build a kindergarten for the youngest citizens of the town. The architect invited students from the Shigeru Ban Studio at Kyoto University of Art and Design, including the author of this thesis, who was in Kyoto at the time to conduct research on the use of paper as an architectural material. The design team consisted of the architect Yasunori Harano, an assistant of Ban's at Shigeru Ban Architects and KUAD University; the architect Mirian Vacari, a Brazilian architect interested in paper architecture; the architect Jerzy Latka and three students: Alexander Riva, Yuta Sakurai and Hoshi Kazufum.

The designers' intention was to erect a semi-permanent building that would last 5-7 years, built on a plan of a 3x3m grid. The building was to be 21 metres long and 6 metres wide (see Fig. 4.99). The building was divided into two classrooms with an interior corridor and the main entrance in between. Initially, the idea was to have columns delineating the 3-metre grid, but later the school teacher decided that columns in the middle of the classrooms would interfere with the conduct of the children's activities. So the columns in the middle were removed from the design and the structure was re-calculated in order to obtain structural stability (see Fig. 4.100).

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FIGURE 4.99 Miao Miao Paper Nursery School, 2014

Before the design was finished, a 1:1 scale mock-up of the connection between the wooden joints and the paper tubes was made (see Fig. 4.101). The mock-up would demonstrate whether it would be possible to reach the bolts with the appropriate tools.

The design process was completed in September 2013. The author, who had already returned to Poland by this stage, received an invitation to the building site in Chengdu and went there in November to help out for a month. Some fifteen volunteers were already involved in the project, divided into two groups. One group went to Taiping, while the other stayed in Chengdu. The first few weeks were devoted to work on the foundations of the building site, the impregnation of paper tubes and the preparation of wooden joints at Liu Yang Architect workshop in Chengdu.

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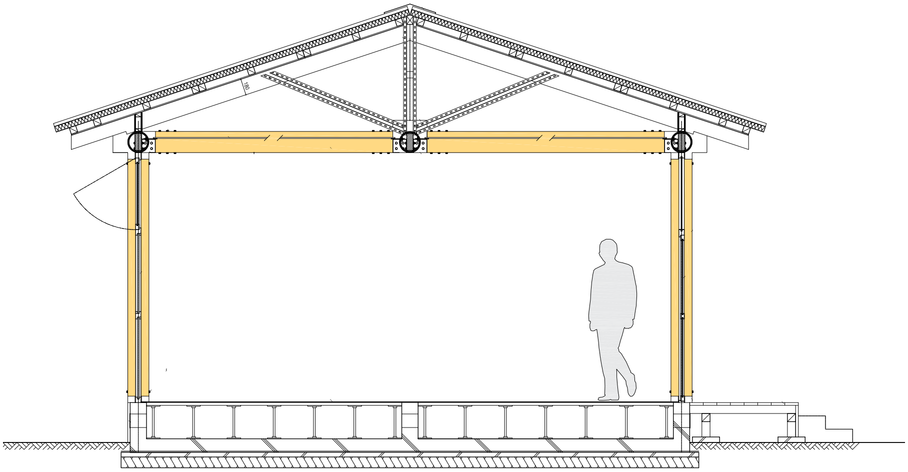

FIGURE 4.100 Miao Miao Paper Nursery School, detailed section, 2013

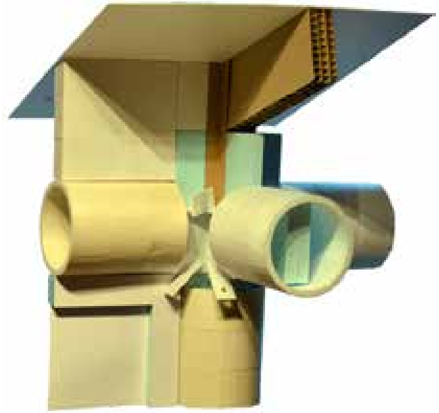

FIGURE 4.101 Miao Miao Paper Nursery School, 1:1 mock-up of the paper-tube connection, 2013

FIGURE 4.102 Miao Miao Paper Nursery School, preparation of wooden joints in Chengdu, 2013

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The wooden joints were created by the second group of volunteers, including the author (see Fig.102). After two weeks' preparation, during which all the wooden elements had been prefabricated and all the necessary components like insulating foam, roof cladding, perforated L-angles etc. had been bought, the volunteers went to Taiping. After they had levelled the base joints (joint A), the erection of the paper tube structure commenced (see Fig. 4.104). Paper tubes had been impregnated in advance by dipping them into polyurethane liquid. The erection of the structure itself was to be a very fast and easy process, especially as the project was designed in such a way as not to use any crane. Unfortunately, some new problems arose, which delayed the construction process. For instance, the steel elements were the wrong colour, and the bracing elements had been threaded incorrectly. After two weeks at the site, the paper tube structure was completed. The next few weeks were devoted to the roof structure, the installation of the wall panels, the interiors and landscaping. The building was opened to the public on 1 April 2014.

FIGURE 4.103 Miao Miao Paper Nursery School, construction of the paper tube structure, 2013

Ya'an Nursery School's structural system consists of paper tubes serving as columns and beams (see Fig. 4.104). The roof structure is a mix of timber and steel perforated L-angles. The paper tube structure was built out of 49 paper tubes with a length of 2,617mm each. The outer diameter of the tubes was 234mm, while the walls of the tubes were 15mm thick. The whole structure was strengthened with horizontal and vertical bracing rods. The bracing brought extra stability in case another earthquake would strike. As paper tubes are flexible and able to hold the lateral and vertical forces caused by an earthquake, other elements made of timber or plastic might break. Steel bracing held the flexible structure of paper tube beams and columns in place. The new structural solution Shigeru Ban wanted to apply in Ya'an Nursery School was dictated by the problems the architect had faced during the construction of Hualin Primary School in Chengdu in 2008. To prevent running the same risk, Ban had proposed cross-like wooden joints made out of laminated timber boards.

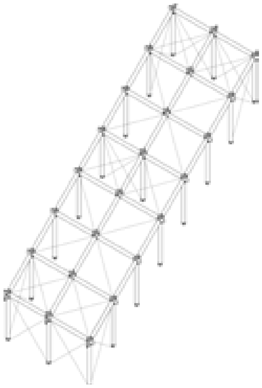

FIGURE 4.104 Miao Miao Paper Nursery School, axonometric view of the structure, 2013

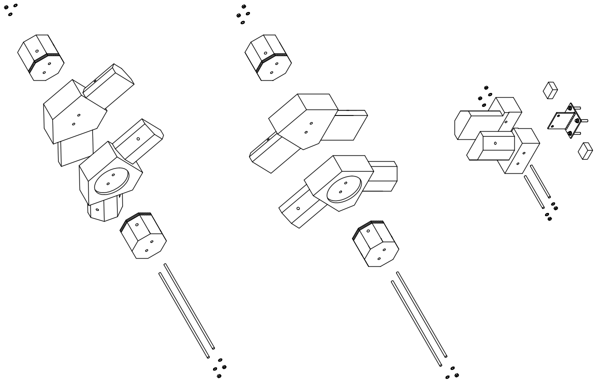

FIGURE 4.105 Miao Miao Paper Nursery School, wooden joints between paper tubes, types: a), b), c) and d), 2013

A new solutions for wooden joints was used in the project. This time the joints were to be prepared by the volunteers at a local workshop. Therefore, they had to be easy to manufacture. Four types of wooden joints were used (see Fig. 4.105). Bottom joint A was used at the base of the columns; top joint B was used to connect the columns, beams and wooden roof structure, located at the side of the building; joints C and D were used to connect the paper tube beams and the steel roof structure in the middle. Joints C and D are different only in that they have a pin for the columns; joint C hangs, while joint D lies on top of the columns. Joints B, C and D are composed of two flat elements which, when inserted into each other, look like a cross with four arms, each at an angle of 90° when viewed from above. Joints are made out of laminated timber with the thickness of 72mm. This type of joints allowed a significant reduction in the weight which resulted in the possibility of connecting joints and tubes in the air (see Fig. 4.107). The joints were fixed together with L-shaped steel plates that were used as a place to attach horizontal and vertical steel bracing. Although the joints required less material and were lighter and easier to produce, they made the entire structure much more complicated, because of the additional steel plates and bracing required.

FIGURE 4.106 Foundations of Miao Miao Paper Nursery School, 2013

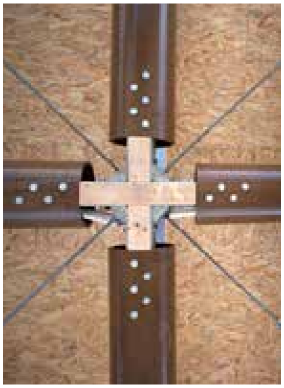

FIGURE 4.107 Wooden joint, type C, 2014

Ya'an Nursery School's foundations were raised up to 440mm from the ground level to prevent the paper tubes from being damaged by water (see Fig. 4.106). This was a lesson learned during Shigeru Ban's previous construction project in the region, Hualin Primary School. Due to the raised foundation, it was possible to create openings in the foundation wall and provide UFAD (Under Floor Air Distribution) so as to lower the temperature inside the classrooms. Steel plates installed beneath wooden joint A keep the bracing rods in place to ensure the building's stability.

The building's walls were made out of PVC sashes with glazing. Panels were fixed to the paper columns through wooden battens screwed to the tubes. The wall was rendered rigid by means of horizontal and vertical bracing, which is present in all spans of the building. Vertical bracings abutted the internal side of the walls.

The roof structure was the most complicated part of the building. It is a mix of wooden beams and perforated L-angles (see Fig. 4.108). The angles had been used in a previous Shigeru Ban project, Atelier for a Glass Artist, built in Tokyo in 2006. The wooden rafters are connected to joint C or D by means of perforated L-angles measuring 35x35mm and 3mm thick. The L-angles are arranged in pairs on either side of the joints. The horizontal bracing rods also pass through the joints. An OSB board layer (oriented standard board or flakeboard) lies on the rafters, with a purling and thermal insulation foam in between. The roof is covered with a layer of steel plates. Large eaves should protect the paper tubes from getting wet due to rain. [20, 26]

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FIGURE 4.108 Paper tube, timber, perforated L-shape and steel bracing composition of the roof structure, 2014

§ 4.3.15 Wikkel House

Authors: René Snel (invention), further developed by Fiction Factory
Year: 1996 (invention), further development: 2012-ongoing
Location: no fixed location
Area: 5m^2 per segment (size: M)
Lifespan: fifty years (with fifteen years' warranty)
Type: Housing

In the late 1990s the Dutch inventor René Snel created the concept for a house composed of several layers of single-face corrugated cardboard. He was inspired to create Wikkel House (wikkel is the Dutch word for 'wrapper') by cardboard transportation crates for tomatoes, which were produced by wrapping corrugated cardboard around a mould and laminating it. Snel created the machine which wrapped segments of the house. Wikkel House was first and foremost designed as a temporary housing solution for areas struck by disaster. Therefore, the machine producing the 'wraps' was attached to the back of the truck, so as to be mobile. By transporting the machine and rolls of corrugated cardboard to disaster-stricken areas, crews would be able to manufacture houses on site. However, none of the non-governmental organisations involved in emergency relief was interested in launching the project, so it was aborted in 2008. A few years later, an Amsterdam-based company called Fiction Factory bought the machine and the intellectual property of Wikkel House and commenced development of the project (see Fig. 4.109). The first house produced by Fiction Factory was exposed to the public at Amsterdam Schiphol Airport in 2012.

FIGURE 4.109 Wikkel House showroom at Fiction Factory, Amsterdam, 2016

Wikkel House consists of prefabricated segments, each 4.6m long and 3.5m high. Each segment is 1.2m wide, in accordance with regular corrugated cardboard production size standards (see Fig. 4.110). Each segment covers a usable area of 5m^2. The segments are manufactured by wrapping and laminating 24 layers of corrugated cardboard, kept in place by wooden frames. The frames serve as the key structural element. Rolled-up corrugated cardboard passes through several rollers that guide it to a conveyor belt, where it is covered in glue. By moving back and forth, the conveyor belt adjusts the tension of the roll, in accordance with the uneven shape of the house.

A braking system determines how tightly the paper is wrapped around the mould. The first layer of cardboard is attached to the two wooden frames. Once 24 layers have been wrapped around the mould, the mould folds inwards and the segment can be taken off the mould. As the lamination process has not yet been completed, and the glue has not yet completely dried, the timber frames act as a mould until the glue has dried completely and the cardboard core has set (see Fig. 4.111).

Next, the segments are covered from the outside with watertight and breathable textile and clad with timber planks, which are screwed to wooden side frames (see Fig. 4.112). On the inside, the corrugated cardboard is covered with plywood. One segment weighs approx. 500 kg. The segments can be transported by flatbed trailer, although only two segments can be transported at a time.

The first example of Wikkel House to be produced was installed at Amsterdam Schiphol Airport. It was covered by an aluminium layer. This was a costly and hard-to-produce solution, so the aluminium was replaced with wooden cladding.

FIGURE 4.110 Wikkel House segments taken off the mould at Fiction Factory, Amsterdam, 2016

FIGURE 4.111 Timber frame and connection with the corrugated cardboard of Wikkel House, 2016

FIGURE 4.112 Timber frame connection and sealing detail of Wikkel House, 2016

FIGURE 4.113 Mock-up of the wall of Wikkel House (section), 2016

FIGURE 4.114 Foundation beam of Wikkel house, 2016

The segments are joined by steel threads that go through the walls and through slots in the wooden frames (see Fig. 4.113). The slots are also used as an exhaust for the moisture resulting from drying glue. Furthermore, the surface is sealed where the various segments connect. Several segments are placed on wooden or steel beams, which are connected to a concrete foot (see Fig. 4.114). The front and back façades

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are made of timber and glass and attached to the timber frames. One full segment is estimated to take one day to produce.

Wikkel House is advertised as an eco-friendly, comfortable, prefabricated summer house that can be installed at any chosen location within one day. It can be fully furnished and equipped with a toilet, kitchen unit and air conditioning system.

The price for a three-segment Wikkel House starts from €25,000. The expected lifespan of the house, according to the information provided by the manufacturer, is fifty years. However, the warranty period is fifteen years, even if in the Netherlands the legal warranty for products of a structural nature is limited by law to ten years.

In Wikkel House the laminated layers of single-face corrugated cardboard serve as the main structural element. The main structure is founded on 24 layers of laminated corrugated cardboard, which serves as the house's floor, walls and roof, all in one. The wooden frame is mainly used to keep the cardboard in place during the production process, as a connecting element and as fail-safe system in case the cardboard core is damaged.

Several interesting tests were conducted while Wikkel House was developed as a graduation project by Casper van der Meer of TU Delft's Faculty of Industrial Design. [27] One of the issues Van der Meer encountered while doing his research for his Master's dissertation was the drying of glue after a segment of Wikkel House had been produced on the mould and taken off the mould. As long as the PVAC glue had not dried, the cardboard core which is the main structural element of Wikkel House would not achieve optimal strength. Therefore, it was necessary to dry the glue in different places after the wrapping process. Three specimens were tested in order to investigate the drying behaviour of the laminated cardboard, which was covered by a membrane foil that was waterproof but moisture-permeable. One sample was left completely exposed, the second was completely sealed off by means of plastic foil, and the third was wrapped in membrane foil. After one week the relative weight of the moisture content had evaporated by 8% in the exposed sample, by 8% in the membrane-covered sample, and by 0% from the sealed-off sample. The test indicated that more moisture evaporated than was actually applied in the form of glue during the lamination process, which meant that the relative humidity of the cardboard itself was higher than expected. Covering the cardboard core with a waterproof but breathable membrane seemed to be the most desirable solution.

Another interesting test Van der Meer carried out was related to the bending of the material. Two different cardboard sandwiches were prepared. One was made out of recycled cardboard, the other out of virgin cardboard. The samples were as long as

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the span of the floor of Wikkel House between two foundation beams, i.e., 1.6m. The width of the samples was 0.4m. The test was first performed 24 hours after gluing. The results showed that even if the glue was not yet dry completely, the sample composed of virgin cardboard could hold 2.3 times more weight (127 kg) than the one made of recycled cardboard (55 kg). The second test was performed one week after the samples had been glued. This time the virgin cardboard could hold 240 kg, well over twice as much as the recycled cardboard (112 kg) and nearly twice as much as the virgin cardboard sample that had not yet fully dried after 24 hours.

The test results indicate the importance of allowing the glue to dry completely before applying full forces to the structure (before transportation, installation on site, furnishing and use). They also indicate that the strength of the house is strongly dependent on the type of cardboard used (virgin or recycled).

§ 4.3.16 Wroclaw University of Science and Technology 70th Anniversary Pavilion

Authors: Jerzy Latka, in cooperation with students from Wroclaw University of Science and Technology
Year: 2015
Location: Wroclaw, Poland
Area: 70.7m^2 (size: L)
Lifespan: six weeks
Type: Temporary event venue/ exhibition

In the spring of 2014, the author of this dissertation was commissioned by the authorities of Wroclaw University of Science and Technology to design and build a pavilion to mark the occasion of the University's 70th anniversary.

The requirements for the pavilion were as follows. It had to be a structure that would be installed in Solny Square in Wroclaw's city centre, adjacent to the Main Square. It would remain there for about two weeks before being transported to the WUST campus, where it would remain for a few more weeks. The pavilion would be used to present WUST's 70-year history (1945-2015). In addition, the pavilion had to be visually attractive – an eye-catcher that would encourage visitors to learn more about the history and development of the University.

Due to transportation capabilities and the amount of time needed for the construction of the pavilion at Solny Square, the decision was made to prepare the pavilion in the

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form of components, which could be transported and assembled on site. The size of each component had to be kept under 2.5m (width), 6m (length) and 4.5m (height) to allow transportation to the city centre by a regular-sized truck.

The commission was the perfect occasion to apply cardboard to a large-scale structure. Therefore, the author designed three proposals for a pavilion, each of which involved the use of paper tubes as a primary or secondary structural material.

Modular Pavilion

The author's first proposal centred on the creation of four hexagonal-in-plan modules, which could be assembled after being transported to the square. The pavilion would have six entrances, allowing people to enter from the most popular directions of the people flow at the square (see Figs. 4.115 and 4.116).

Each of the modules was composed of 15 frames made out of paper tubes connected by wooden joints (see Fig. 4.117). The space created by the frames would be used for an exposition of posters hung up on the walls. Since the exhibition could be experienced in a non-linear way, a special scenario would have to be created for the exhibition. Semi-circular spaces outside the pavilion would be used for a further presentation of the University's achievements in the form of mock-ups or additional posters.

The pavilion would be transported in form of curved wall components, connected at the top and bottom by wooden beams. Then the wall components would be connected by means of horizontal paper tubes, thus creating the modules.

The maximum height of the pavilion would be 2.65m (see Fig. 4.118). Five different types of paper tube frames would be involved, with different widths but the same heights. The triangles, created at the centre of the modules, would be covered with a translucent PVC membrane (see Fig. 4.119). A total of 171 paper tubes would be incorporated into the structure, whose external size would be 11x13m.

FIGURE 4.115 WUST Pavilion, version 01, site plan, Jerzy Latka archi-tektura.eu, 2014

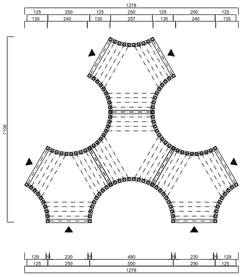

FIGURE 4.116 WUST Pavilion, version 1, plan view of the whole pavilion, 2014

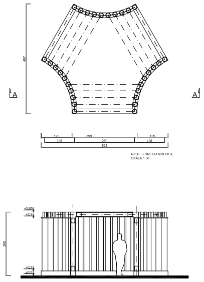

FIGURE 4.117 WUST Pavilion, version 1, plan view and section of single segment, 2014

FIGURE 4.118 WUST Pavilion, version 1, visualisation from the outside, 2014

FIGURE 4.119 WUST Pavilion, version 1, visualisation from the inside, 2014

Social Pavilion

The author's second idea for a pavilion centred on a long and narrow curved corridor composed of paper tube frames. The pavilion would be positioned in such a way as to ensure its entrances faced the main flow of people walking from the Main Square to Solny Square (see Fig. 4.120). The exhibition would be experienced in a linear way. A semi-circular patio covered with delivered grass in rolls would create a social space equipped with cardboard furniture, lending the city centre some added grandeur (see Fig. 4.121). The combination of four modules would result in the pavilion being question-mark-shaped. Each module was in plane a part of a pentagon with circle cut out in the middle. There were 65 frames, composed of paper tubes and wooden joints, with nine different heights (see Fig. 4.122). The pavilion would be 2.20m at its lowest points and 2.80m at its highest point. Prefabricated wall components in the form of paper tubes connected at the bottom with wooden foundations and at the top with wooden beams would be transported and assembled at the Square (see Figs. 4.123 and 4.124). The overall external dimensions of the pavilion were 16x9.3m.

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FIGURE 4.120 WUST Pavilion, version 02, site plan, Jerzy Latka archi-tektura.eu, 2014

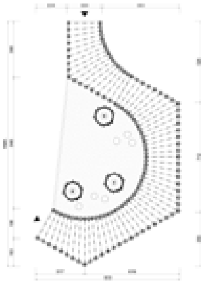

FIGURE 4.121 WUST Pavilion, version 2, plan view of the whole pavilion, 2014

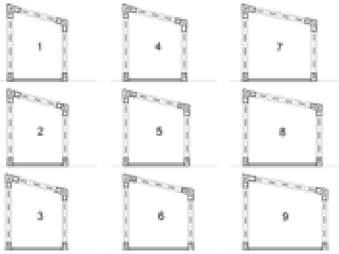

FIGURE 4.122 WUST Pavilion, version 2, different paper tube frames, 2014

FIGURE 4.123 WUST Pavilion, version 2, visualisation view from Main Square, 2014

FIGURE 4.124 WUST Pavilion, version 2, visualisation – view from inside, 2014

Interactive pavilion

The third concept was different from the previous ones in both shape and structure. In this proposal the main structure was composed of wooden arches and paper tubes attached perpendicular to the centre of the arches (see Figs. 4.125, 4.126 and 4.127). The design involved a total of 498 paper tubes, each illuminated by a LED strip with full RGB colours. The paper tubes were 600mm long and had a diameter of 275mm. Their walls were 10.5mm thick. The paper tubes were sealed at the top and bottom by circular Plexiglas plates. Eighty of the tubes were used to hang exhibition boards from. Information about the University was printed on Plexiglas boards attached to the lower half of the tubes.

The exhibition was organised in two linear arrangements on either side of the pavilion. One side of the pavilion showed the development of the University, while the other side showed important moments in its history. The boards placed closer to the floor were designed for children, while the ones placed at a higher level were intended for adults.

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The pavilion consisted of six components in the form of semi-circular tunnels (see Figs. 4.142 and 4.143). Each of the components was composed of six laminated timber arches with a radius of 2,350 to 2,650mm (see Fig. 4.128). Different-sized arches allowed the architect to achieve a curved surface of the lit skin made out of paper tubes (see Figs. 4.129, 4.130). The components were small enough to be transported to the city centre by low-bench truck (see Fig. 4.142). After assembly, the size of the pavilion was 11,5x6,15m (see Fig. 4.125).

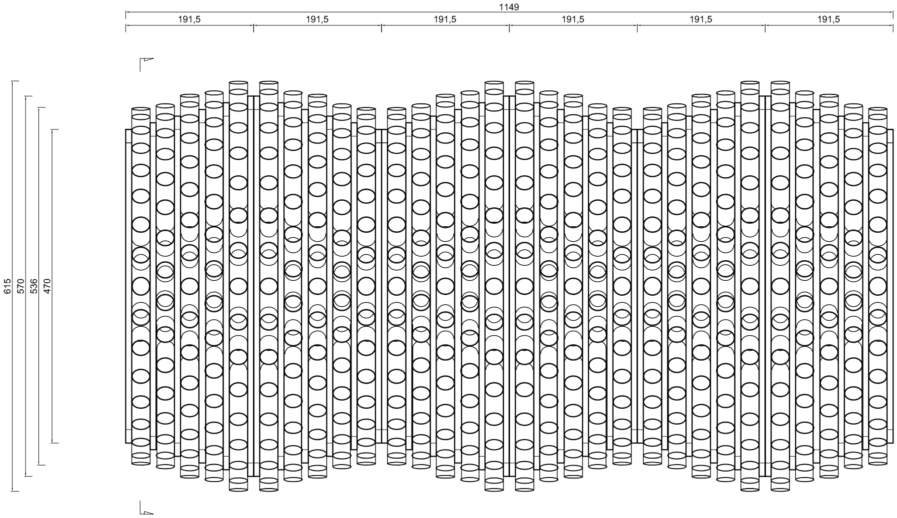

FIGURE 4.125 WUST Pavilion, version 3, plan of the pavilion, 2014

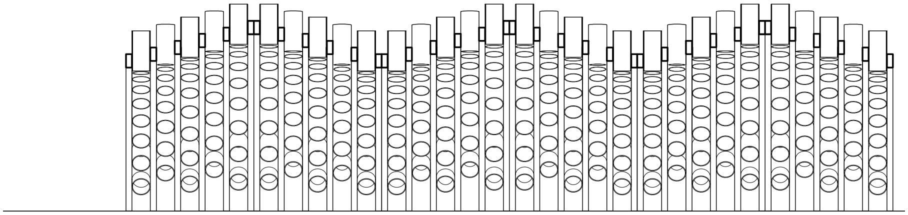

FIGURE 4.126 WUST Pavilion, version 3, section of the pavilion, 2014

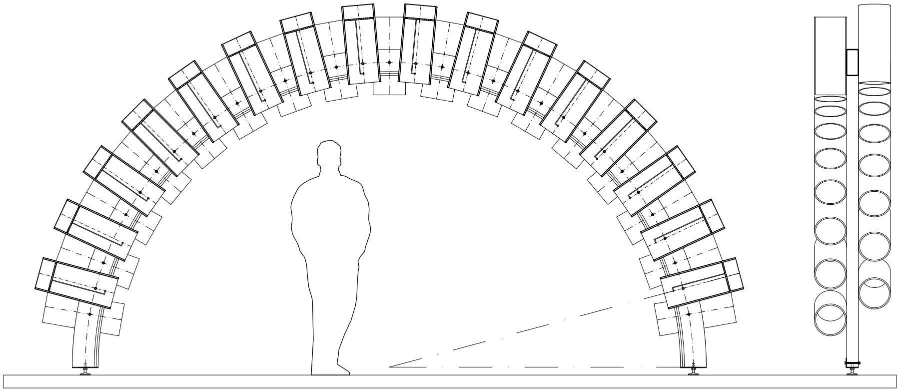

FIGURE 4.127 WUST Pavilion, version 3, detailed section, 2014

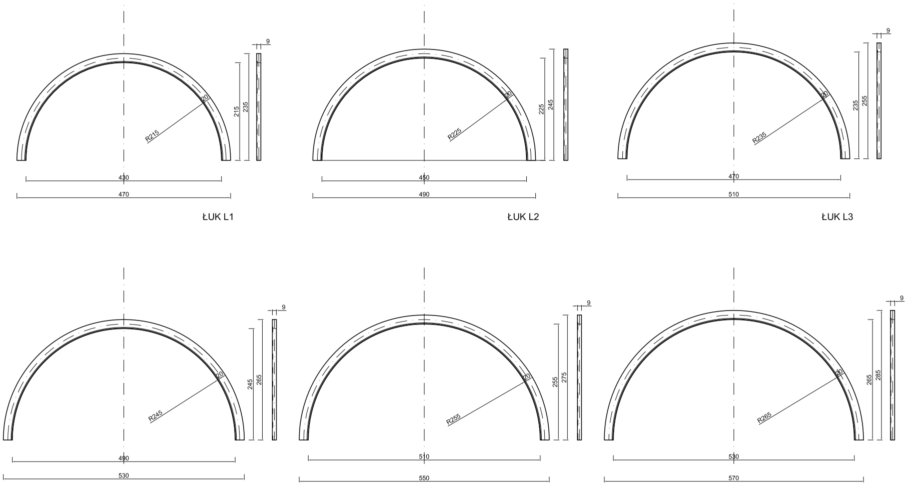

FIGURE 4.128 WUST Pavilion, version 3, different-sized arches for pavilion construction, 2014

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FIGURE 4.129 WUST Pavilion, version 3, model of the pavilion, 2014

FIGURE 4.130 WUST Pavilion, version 3, model of the pavilion - entrance, 2014

It was the third idea that was selected for execution. Therefore, it was necessary to create a team consisting of specialists representing different specialities in order to proceed with the construction, electronic equipment installation, exhibition and dynamic illumination of the pavilion.

Four scientific organisations for students attending Wroclaw University of Science and Technology were invited to cooperate. They were the following organisations:

The Humanisation of the Urban Environment organisation affiliated with the Faculty of Architecture. The students making up this organisation were responsible for the general execution of the pavilion and for the exhibition scenario. The exhibition group was led by Monika Pietrosian and consisted of Marta Jastrzebska, Dorota Reclawowicz, Anna Kwapien, Anna Mlodzianowska, Jarosław Kuziemko, Aga Folaron and Bartosz Kołodziejczuk. The members of the general contractor group were led by the author of the pavilion. This group consisted of Katarzyna Dominiak, Karolina Dyjach, Anna Pastor, Emilia Karwowska, Adrianna Kazmierczak, Patrycja Jedra, Marta Gruca, Malgorzata Radaj, Marta Wroblewska, Maciej Marszal, Marta Mochniak, Justyna Romanowska, Krzysztof Gorczakowski and Agnieszka Ejsymont.

The EtaKsi science organisation, affiliated with the Faculty of Civil Engineering, was responsible for the structural stability and transportation of the pavilion. This team was led by Anna Gorska and the group consisted of Adrian Jakubowski, Malgorzata Soroko, Adam Sterniuk, Agnieszka Helik, Justyna Kiedrzyn, Adam Banasiak, Bartosz Bartczak, Michal Gaj, Dawid Sionkowski, Michał Plotka, Mateusz Bienkowski and Wioletta Michalik.

MOS (Microsystems-Oriented Society), affiliated with the Faculty of Electronic Engineering, dealt with the electronic wiring and LED lighting control system. The team consisted of Michal Chodzikiewicz (coordinator), Liliana Cierpial, Emiliana Cierpial, Marcin Czekajlo, Piotr Falis, Igor Gajewski, Patryk Gasek, Martyna Giler, Tomasz Januszewski, Piotr Kowalczyk, Damian Krata, Daniel Majchrzycki, Grzegorz Muraczewski, Marcin Panek and Adrian Pralat (second coordinator).

LabDigiFab, affiliated with the Faculty of Architecture, was responsible for the illumination-controlling software. The team consisted of Jakub Lawicki (coordinator) and Paweł Joniak, Emil Barczynski and Bartosz Witkowski.

Students from TU Delft's Faculty of Architecture and the Built Environment participated in the construction, as well, during their stay at WUST in April 2015: Alois Knol, Arko van Ekeren, Erik van den Broek, Iris van der Weijde, Marijn Verlinde, Dion Renzo, Adhir Lachman, Eline Stubert, Max van den Berg, Maarten van der Kuur, Roman Oost and Wouter Kamphuis.

The pavilion was realised in association with partners and sponsors who contributed funds, materials and knowledge.

After the execution drawing had been finalised, the teams rented WUST's production hall. All the materials needed for construction were delivered here. Next the impregnation tests were carried out. As the paper tubes were not protected from external conditions and the weather, a waterproofing method had to be selected very carefully. Based on previous experiences as well as on tests conducted previously by the Humanisation of the Urban Environment students' organisation, several impregnators available on market were selected for testing. The specimens of the paper tubes were coated with six different products:

- Epidian – an epoxy composition.
- Syntilor – BSC varnish for wood based on polyurethane resins.
- Liquid glass.
- Domalux – yacht varnish based on alkyd-urethane resins.
- Bondex – exterior & yacht – polyurethane-based varnish used on wooden parts exposed to constant contact with water.
- Sarsil H-14/R silicone-based reagent for waterproofing walls and building materials.

The specimens were subjected to direct contact with water by means of a one-hour shower and by being put into a bucket with water for 24 hours. The results showed

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that the paper tubes were prone to damage caused by water in two ways. One source of vulnerability was the cut endings of the tubes, which were however protected by circular Plexiglas boards attached to either end of the tubes by silicon glue and a few thin nails. Secondly, the walls of the tubes were prone to damage. Specimens coated with epoxy resin showed good results: neither the walls nor the cut ends were damaged. However, the process of applying the coating was time-consuming. The epoxy had to be mixed before being applied to the material with a hardener. Moreover, it required a longer drying time than other impregnators. Furthermore, epoxy is harmful to people's health and to the environment (see Fig. 4.131). The second type of varnish used, Syntilor, based on polyurethane resins, covered the outer layer of the tubes quite well. However, it still allowed the cut ends of the paper tubes to be damaged by water (see Fig. 4.132). Liquid glass proved insufficiently able to protect either the outer layer or the cut ends, even if it did have the added bonus of extra fire protection (see Fig. 4.133). The Domalux product (normally used to impregnate yachts) proved unable to protect the tubes from water. The paper tube treated with this product grew soft and the layers of paper delaminated easily (see Fig. 4.134). The polyurethane-based Bondex yacht and wood varnish did well at protecting both the outer layer and the cut ends of the specimens. It changed the appearance of the tube by making it darker and shiny, but the coating seemed to be firm and well absorbed by the layers of paper (see Fig. 4.135). Lastly, the Sarsil reagent for building materials proved to be insufficiently strong. It caused the paper tube to delaminate easily and to lose its strength, allowing it to be torn easily (see Fig. 4.136).

Since the best results were achieved by Bondex, this was the team's product of choice.

FIGURE 4.131 Impregnation specimen No. 1: Epidian epoxy coating, 2015

FIGURE 4.132 Impregnation specimen No. 2: Syntilor wood varnish, 2015

FIGURE 4.133 Impregnation specimen No. 3: Liquid glass, 2015

FIGURE 4.134 Impregnation specimen No. 4, Domalux – yacht varnish, 2015

FIGURE 4.135 Impregnation specimen No. 5, Bondex – exterior & yacht varnish, 2015

FIGURE 4.136 Impregnation specimen No. 6, Sarsil reagent for waterproofing, 2015

As the paper tubes were mounted into position perpendicular to the centre of the arches, they were subjected to flat crush compression. A project partner, Corex Group, and VPK Packaging Group, producers of paper tubes and packaging materials, conducted flat crush tests on the paper tubes. These tests were conducted in accordance with the following norms: ISO 11093-1 (selecting the specimens), ISO 11093-2 (preparing the specimens) and ISO 11093-9 (strength test). Each specimen had a diameter of 100mm. Three specimens were tested, with the following results: 793N/100mm, 783N/100mm and 862N/100mm. The average flat crush test result was 813N/100mm. The expected strength was 650N/100mm +/-10% (see Fig. 4.137).

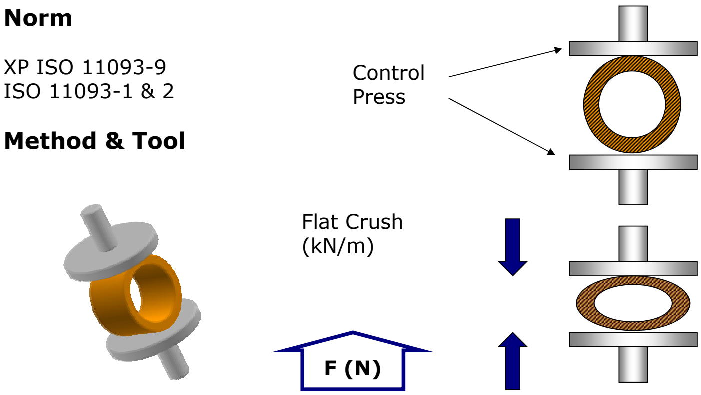

FIGURE 4.137 Schematic representation of flat crush test conducted by Corex Group, 2015

Production of the pavilion's components commenced in April 2015, when all the necessary materials were received and tests were conducted. First the paper tubes were drilled, then impregnated by dipping them into the polyurethane-based Bondex exterior & yacht varnish (see Fig. 4.138). After being dipped into Bondex, the paper tubes were hung from wires to dry (see Fig. 4.139). At the same time, the timber arches were prepared by drilling the holes for the paper tubes and other structural elements. In the initial draft, the pavilion was placed on adjustable levelling feet. However, due to the need for extra weight, the levelling feet were replaced by foundations in the form of serrated wooden beams protected from below by a rubber cloth and placed on the ground (see Fig. 4.140). The electrical wiring was placed in milled slots in the wooden arcs. Then the wooden arches were connected to the paper tubes by means of bolts (see Fig. 4.141). Although the test results indicated that the paper tubes were strong enough for a flat crush, some additional steel pipes were used against compressive and tensile horizontal forces.

FIGURE 4.138 Impregnation of the paper tubes, 2015

FIGURE 4.139 Allowing the impregnated paper tubes to dry, 2015

FIGURE 4.140 Preparing the wooden foundations, 2015

FIGURE 4.141 Electrical wiring, 2015

The assembled components were transported to the city centre one by one, then installed on Solny Square by means of a crane (see Figs. 4.142 and 4.143). Over the next three days, the LEDs were installed, as were the exhibition boards. In early May the Pavilion was opened to the public (see Figs. 4.144 – 4.148). The pavilion was incorporated into the programme for Wroclaw's European Night of Museums. After housing the exhibition on Solny Square for two weeks, the pavilion was transported to the campus of Wroclaw University of Science and Technology (see Fig. 4.149). Several weeks later the pavilion was disassembled. The paper tubes were discarded, while the wooden arcs were preserved for another experimental project.

FIGURE 4.142 Transportation of the components to the city centre, 2015

FIGURE 4.143 Placement the pavilion components on Solny Square, 2015

FIGURE 4.144 Visitors: Maria and Filip, 2015

FIGURE 4.145 Detail of the exhibition boards, 2015

FIGURE 4.146 WUST Pavilion on Solny Square, Wroclaw, 2015

FIGURE 4.147 The pavilion on Solny Square at daytime, 2015

FIGURE 4.148 The pavilion on Solny Square at night, 2015

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FIGURE 4.149 The pavilion on the Wroclaw University of Science and Technology campus at night, 2015

The Pavilion realised in order to commemorate Wroclaw University of Science and Technology's 70th anniversary was an experimental project realised in cooperation with specialists from different fields of science and industry. The main challenge involved in the project was proper communication between designers, contractors, the university's administrators and other parties involved in the process. The key issue encountered in the early days of the project was accurate and precise directions. For instance, the phrases 'It will be finished soon' or 'It will take several days' turned out to have different meanings for the architect on the one hand and for the engineers associated with the Faculty of Electronical Engineering on the other. This resulted some unexpected delays setting the realisation of the project back several days. The designers and contractors also took a different approach to the aesthetics of the project. While for the architects, the purity of the structure and the natural appearance of the materials were paramount, the most important aspect to the civil engineering students was the stability and protection of the structure. Apart from these small misunderstandings caused by different styles of communication, the project was carried out smoothly and every single person involved in the project was completely engaged. Without the high level of engagement shown by the students and the University's administrators, the project would not have succeeded.

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Due to time and budgetary restraints, it was impossible to conduct long-term impregnation tests on the tubes. This resulted in some paper tubes being damaged after having been exposed to natural conditions and rain for over a month. Another event the architect had not allowed for was the visitors' behaviour. Many people at Solny Square and on the university's campus treated the pavilion like a big toy. They tapped on the Plexiglas plates as if they were drums that needed to be played, which resulted in the boards falling off, thereby exposing the cut ends of the paper tubes.

Despite the aforementioned issues, the Pavilion and the process of designing and constructing it were successful, and both the designer and his team learned some valuable lessons.

§ 4.4 Conclusions

People have tried for almost 150 years to use paper and its derivatives as building materials. Different approaches have been taken over the course of time. Since machine production of paper was invented in the late eighteenth century, the material has been recognised as a cheap substitute for existing construction materials – particularly for wood. The invention and popularisation of new products in the paper-making industry, such as corrugated cardboard, paperboard and honeycomb panels, have encouraged architects and engineers to experiment with new structural and material solutions. In the 1980s, Shigeru Ban introduced paper tubes as building components, and it soon became the most popular paper-based product used in architectural structures.

Early examples of the use of paper in architecture (late nineteenth century to the late 1980s) concerned mainly emergency relief houses, especially after World War II, when there was a considerable housing shortage. Most of the projects then carried out were of a temporary nature. However, some of them lasted surprisingly long. One experimental shelter built by the Institute of Paper Chemistry in 1944, designed to last one year, ended up lasting 25 years.

Through much trial and error, other interesting proposals were made, designed to provide a proper answer to the demand for affordable housing and shelters. Such proposals included the Pappedern – recreational and utility units designed by 3H Design for the 1972 Munich Olympics.

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The development of cardboard as a building material was largely the result of activities carried out by Richard Buckminster Fuller, who was always on the look-out for new and innovative solutions to the housing problem. His experiments with geodesic domes built out of cardboard panels turned the public on to the construction possibilities presented by cardboard.[28]

Approaches to paper as a building material have changed noticeably over the course of time. In the twentieth century, paper products were recognised as a material that is both cheap and easily obtained. Therefore, a great deal of work was done with regard to impregnation methods or the composition of sandwich panels made out of cardboard and other materials like aluminium sheeting, GRP, sulphur, resin or plastic coating, especially since the second half of the twentieth century, which saw the development, introduction and use of different types of plastics (e.g. films) and surface treatment as a moisture barrier. The changed composition of paper and the development of new coating methods made paper a more promising material for buildings with a longer lifespan.

In the last decade of the twentieth century, architectural requirements changed in accordance with Agenda 21, an action plan drawn up after the 1992 Earth Summit (UN Conference on Environment and Development) in Rio de Janeiro. [29] The document, which outlines the meaning of sustainable development in conjunction with a growing consciousness of the limitations of non-renewable resources, brought 'pro-ecological' architecture into general use. As a result, paper, a material produced from cellulose fibers that can be obtained from renewable resources and can be recycled up to five life cycles, gained a great deal of popularity. The Agenda 21 action plan also had an impact on the impregnation methods used. The end of the twentieth century brought us a greater understanding of paper structures, which are now recognised as being sustainable and 'green'.

Thanks to its light weight, low price and ease of production, and also thanks to its sustainable properties and rather ephemeral character, designers are now more likely to use paper in several main categories.

This thesis presents 31 projects involving paper architecture. These largely fall into four categories:

- Emergency shelters and emergency relief structures (ten projects);
- Affordable and sustainable houses (six projects);
- Structures for temporary events (five projects);

- Experimental and commercial projects (ten projects, including six permanent structures and four short- or medium-lifespan structures).

Some of the projects realised fall into more than one category. For example, the projects undertaken by Richard Buckminster Fuller could be categorised as experimental projects, but the architect always kept an eye on quality of life, and his own project was inspired by a human-centric point of view. Therefore, these projects can also be categorised as affordable and sustainable houses.

Since paper is a cheap material, most of the projects presented here were obviously emergency, relief or low-price housing structures. Actually, most of the first attempts to use paper as a structural material in architecture focused on emergency housing. Other proposals concerned short- or medium-lifespan structures that served as homes or places for social gatherings or utility buildings (Pappedern, Paper Dome). Pavilions and exhibition spaces make up another category of paper structures.

One of the biggest issues with using paper in architecture is the fact that few places have authorised the use of paper as a building material. There is barely a ‘body of knowledge’ where the knowledge and insights gained in successful projects are collected. Paper is barely recognised and approved as a construction material by institutions, building laws and governments. This means that every time a paper structure is going to be erected, material tests have to be conducted in order to prove its stability and safety. So far only two countries (Japan and Germany) have authorised paper as a building material, and two other countries (the Netherlands, England) have granted permission to build permanent buildings made of paper. Westborough Paper School in Westcliff-on-Sea in the United Kingdom is the earliest European example of paper being approved for the construction of a permanent structure, although the school was designed and built as a semi-permanent or medium- lifespan building, with an anticipated lifespan of twenty years. In the Netherlands, where the roof structure of Ring Pass Field Hockey Club’s clubhouse is made out of paper tubes forming a space frame, authorisation by the local authorities drew upon the high trust gained by the Octatube company during several dozen years of successful activity.

It is hard to predict how certain paper products will behave, especially when they are made of recycled material. Therefore, each time a series of products is manufactured, it must be subjected to testing in order to check for quality differences in the material. The predictability of the quality of the material depends on the production process used, as well as on the source material. Therefore, it is hard to certify material whose properties can vary, even if it comes from one and the same factory. Paper and its derivatives also pose another problem, which is their mechanical properties. Creeping

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and vulnerability to humidity, water and fire are the most problematic issues. There are no known examples of paper structures being used to construct multi-storey building. It may be assumed that paper should only be used for structures of single-storey buildings.

§ 4.4.1 Types of the buildings and characteristics

Most paper structures that have been realised so far are temporary ones. Their lifespan ranges from several weeks (Apeldoorn Theatre) to several years (Hualin Primary School). Only few buildings have been erected to be permanent structures or have a medium lifespan (up to twenty years). This is because the material has not yet been authorized by the building industry, and because of the short-lived nature of paper. For example, the paper tubes used to construct Hualin Primary School have to be painted every year. The recyclability of paper that gives it such a temporary nature provides us with a wide range of opportunities with regard to short-lifespan houses or temporary structures. The other possibility is to use cardboard as a primary (temporary) structure which can be later reinforced with another material, e.g. concrete sprayed onto a cardboard mould. A characteristic feature of permanent buildings is that their paper structural elements are never exposed to the elements. Rather they are used as internal structures, covered by other parts of the building.

Out of all the projects presented in this chapter, only four were made in large quantities. No fewer than one thousand versions of Plydom accommodation for seasonal workers (1966) were produced. Paper Log House was erected in four different locations, with the house differing slightly from its previous incarnations each time, depending on local conditions. The idea of the Paper Dome was employed in four different projects: Dutch Paper Dome, Keio University's Ban Lab Studio, Shigeru Ban's temporary office at Centre Pompidou, and Shigeru Ban Studio at Kyoto University of Art and Design. Each time it was adapted to new conditions. Lastly, Wikkel House is promoted as the first series-produced cardboard house in the world. Many attempts at getting large projects off the ground got stuck in the prototype phase and did not succeed because of a lack of interest on the part of potential stakeholders, or because the market was not ready for it. Furthermore, many potential clients, not to mention local authorities, distrust the reliability of paper and cardboard as a building material. Therefore, the promotion of paper as a sustainable and affordable material should run parallel to new experiments and developments.

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§ 4.4.2 Structural systems

There are three different structural systems with which cardboard architectural elements can be realised [30]: rod systems, panel/plate systems and shell systems.

1. **Rod structural systems** are mainly composed of long slender elements, such as paper tubes or L- and U-shapes. Such systems are composed of:
    a. **Columns** – in the form of paper tubes or U- and L-shapes (Paper Log House, Paper House)
    b. **Columns-and-beams** – in the form of paper tubes or folded cardboard beams (Miao Miao Paper Nursery School)
    c. **Frames** – rod structural system composed of paper tubes or other cardboard materials with stiff connections between the elements (Hualin Primary School, Cardboard House)
    d. **Arches** – in the form of curved elements or straight connected elements such as paper tubes (Dutch Paper Dome, KUAD Studio)
    e. **Trusses** – rod structural system composed of paper tubes or other cardboard elements (Library of a Poet)
    f. **Space frames** – a structural rod system, truss-like structures in which paper tubes are composed in a geometric 3D pattern (Ring Pass Field Hockey Club).

2. **Panel or plate systems:**
    a. **Flat plates** composed of honeycomb panels (Nemunoki Children's Art Museum)
    b. **Folded plates** composed of honeycomb panels (Westborough Primary School).

3. **Shell systems:**
    a. **Single-layered** triangulated network domes (IJburg Theatre – although this could also be regarded as a single-layered space frame)
    b. **Cylindrical shells** (Apeldoorn Theatre)
    c. **Two-dimensional shell** (Wikkel House)
    d. **Three-dimensional grid shells** (Japanese Pavilion for Expo 2000).

§ 4.4.3 Paper products and their use in building

The paper and paper-derived products used in architectural structures are corrugated cardboard, paper board, honeycomb panels and paper tubes. These elements were previously described in Chapter 2.

Earlier examples of paper architecture were composed mostly of paper board and corrugated cardboard. Later architects also began to incorporate paper tubes and honeycomb panels into their designs. It is important to note that paper is always combined with other materials, so that its best qualities can be used without having to compensate for its weaknesses. In some cases the paper structure is enhanced with other building components. Although there is a challenge to use as much paper as possible in order to make the structure more eco-friendly or cheap, this architectural Puritanism is not always found profitable.

Plate products like corrugated board or honeycomb panels work efficiently as wall or roof elements, whereas paper tubes can be used most efficiently when employed as load-bearing slender structures. However, plates can also be used as structural elements of a building when they are incorporated with other members, as shown in the Westborough School or Nemunoki Children's Art Museum. In Apeldoorn Theatre, corrugated cardboard was used as a load-bearing material that covered a 12m span. However, when a greater span is required, usage of more slender and stiffer elements is recommended. On the other hand, the Paper Log House project showed that paper tubes can also be turned into a wall component by being placed right next to each other. Although the paper tubes were rendered more rigid by means of crumpled paper (in Turkey) in order to benefit from the thermal insulation, the connection between the tubes was linear and thus thermal bridges came into being. Plate products, when used as a wall or as roof elements, can be incorporated into sandwich panels. An external layer of a protective material such as polyethylene, aluminium, impregnated solid boards, fibre boards or plastic foils is an optional solution. Plates can also be altered by means of insulating material, such as polyurethane foam.

Due to the properties of paper products (e.g. creep when an element is subjected to constant loading), it is generally better to use short elements rather than long ones. In the Japan Pavilion created for Expo 2000, two long paper tubes (each 20m long) were connected, while 40m long elements were used as structural components. Due to the risk of paper tubes creeping over time, the structure was strengthened with timber-laminated ladders serving as a sub-supporting structure, thus ensuring that the cardboard tubes were a secondary rather than a primary structure. This was enough to guarantee the structure a five-month lifespan. Another example is the Cardboard

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Cathedral in Christchurch, New Zealand. Designed by Shigeru Ban for a city that was greatly damaged by a 2013 earthquake, the church has a roof made out of 16m long paper tubes with a diameter of 600mm. Since the material was not strong enough to carry the loads, wooden beams were inserted into the paper tubes (see Fig. 4.150).

FIGURE 4.150 Cardboard Cathedral in Christchurch, New Zealand, Shigeru Ban, 2013

An important task during the process of designing paper structures is deciding on the location of the paper-based structural elements within the building. Since paper can be damaged by water, all paper elements that serve as structural parts of a building must be protected from the weather, in the construction stage as well as afterwards, once construction has been completed. In the Miao Miao Paper Nursery School project, the paper tubes were aligned with wall panels made out of plastic sashes. This resulted in relatively long roof eaves that had to protect the tubes from the rain. The opposite can be seen at Ring Pass Field Hockey Club, where all the tubes making up the space frame are inside of the building. Therefore, the tubes did not require heavy coating. In fact, some of them were left untreated by way of test. Moreover, in the Miao Miao building, there are few connections between the paper tubes and the wall panels, since the paper tubes are round in section, while the wall panels are square. Additional wooden battens had to be screwed into the paper tubes to make sure the wall panels could be installed.

§ 4.4.4 Connection types

There are six general types of connections between the structural parts of buildings made of paper. They are:

1 **Lamination**

2 **Screw/bolt connections to the joint elements (bracing)**

3 **Post-tensioned elements**

4 **Interlocking**

5 **Folding**

6 **Clipping/tiding**

The process of lamination appears to be the most suitable connection for paper and cardboard. As far as strength is concerned, the layers of the material are best connected when the layers are laminated surface by surface. Different types of glue are used for this purpose. The most popular type is PVAc glue (polyvinyl acetate), also known as wood glue. There are four grades of wood glue, with grade 4 being waterproof. Other adhesives like epoxy, phenol-formaldehyde and polyurethane like PVAc are based on non-renewable resources. The natural bio-based adhesives are polysaccharides and proteins. Both are commonly used in paper production. Currently the development of polysaccharides is prioritised due to their natural origin and structural variability. As polysaccharide adhesives are not intrinsically waterproof, the chemical industry is placing great emphasis on research on this particular subject. [31] Another adhesive is liquid glass, which is used for the production of certain types of paper tubes. Liquid glass is not only used for its adhesive properties; it is also used in fireproof products. However, liquid glass also comes with a disadvantage, which is that during the lamination process it often requires special treatment (e.g. a drying chamber). Furthermore, it is time-consuming.

In the project of the paper house designed and built by Paul Rohfls, structural elements like walls and parts of the roof were laminated. The corners of the walls were first folded, then glued. The walls and parts of the roof were composed of laminated honeycomb panels. In the Westborough Primary School project, the honeycomb wall panels were laminated to the wooden frames. The frames were later connected with

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each other and other components of the building by means of simple screws. Likewise, the process of lamination played a prominent part in Wikkel House, whose walls, floor and roof are made out of laminated layers of corrugated cardboard. Although lamination is the most natural way to treat paper structures, it is time-consuming. The Wikkel House case showed that proper drying time is vital to the strength of the structure, with corrugated cardboard that had not yet completely dried proving to be almost twice as weak as corrugated cardboard that had been allowed to dry properly.

Screw/bolt connections between paper or cardboard elements have their pros and cons. Paper is weak when point loads are applied. Thus the structural elements or components have to be connected by means of specially designed joint elements. If we look at the paper buildings that have been realised thus far, we will find that this type of connection has been the most popular. The joint elements may be plates that are clipped to both sides of the paper (plate) elements, or alternatively, they may be boxes, pegs or planks that are inserted into or between the paper elements. The joints can be made out of timber, aluminium or steel. Other materials such as cast cardboard or other composites may be used, as well. However, paper itself has never been used as part of a connection because of the concentrated forces exerted on the connector. Connections involving screws are disposable. Once a screw has been drilled into the wood, it is not possible to re-use it since the thread of the relatively soft material has been damaged. Bolt connections are re-usable. In his first three structures based on the principle behind the Paper Dome, Shigeru Ban used timber connectors and screws. In the Kyoto University of Art and Design studio, the architect used steel plates as he knew that the building was just temporary and would be moved to another location after his dismissal from the University. It is also important to pre-drill paper elements when using screws and bolts. Pre-drilled holes have to be impregnated before actual construction can commence. Another issue that may occur when connecting paper with elements made of steel, such as screws or bolts, is condensation and the capillary effect caused by the differences in temperature between the cold steel elements and the warmer paper components. To prevent this from happening, an air cavity should be created, and screws should be inserted from the inside i.e. the warmer side. The connections between cardboard elements such as paper tubes and timber joints can be flexible if the structure is built in an area that is prone to earthquakes. However, this often requires additional bracing of the entire structural system. Another issue is the cost of connections. Timber joints are relatively cheap and can be produced manually (as was the case in the Miao Miao Nursery School project) or in a more industrialised setting, by means of computerised cutting of plywood. On the other hand, steel or aluminium joints have to be cast, and they may well end up heavier and more expensive than the paper structural elements. Last but not least, timber is a material that used to live, meaning it has a special aesthetic connection to paper.

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Post-stressing or post-tensioning cardboard elements like paper tubes has proved to be an efficient way to connect elements, because the paper tubes do not have to be connected by bolts or screws. As a result, point loads are avoided and the paper tubes do not need to be pierced. In the first permanent structure in which paper tubes were employed as load-bearing elements (the Library of a Poet), post-tensioned bracing was used. Threaded rods run through the paper tubes as well as diagonally from the wooden joints. A similar solution was applied in the Demountable Paper Dome and Ring Pass Field Hockey Club, but in these projects the elements were post-stressed before being combined with joints. In this type of connection, the tubes are subjected to compression forces, so there is never any tension, which is the best way of make use of their properties. Although this type of connection is effective, it is limited to products like paper tubes. For its part, post-tensioning of building components was used in the Paper Log House and Wikkel House. Paper Log House's wall, composed of paper tubes, was tensioned by a steel rod that ran horizontally through the paper tubes. In the case of Wikkel House, whole segments were connected to each other by a tensioned threaded rod.

Interlocking is an easy type of connection and does not intrude on the material. However, connecting the building components by interlocking requires material with the right level of stiffness and thickness. The case of the Cardboard House built in Sydney shows a wine-box-like connection, which can be assembled and disassembled by several people in a few hours. However, this type of connection has to be reinforced by additional elements like plates or canvas that will not allow the elements to slide out of each other. Furthermore, when the interlocking connection method is used, point loads may occur.

The last two types of connections – folding and clipping/tiding – are the least effective. As far as the aforementioned case studies are concerned, the Japan Pavilion for Expo 2000 is a representative of this type of connection. Its long, overlapping paper tubes were connected by fabric tape to allow three-dimensional movement and rotation during the erection process. The tape worked mostly against shear forces.

§ 4.4.5 Connection with the ground

The permanent paper structures presented in the case studies were predominantly built on concrete foundations. However, sometimes the amount of concrete used can give a wrong impression of how sustainable the paper-based structures actually are. The case of Westborough Primary School, whose concrete slab amounted to 85%

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of the weight of the whole building, shows a significant disproportion and deviation from the architects' original idea. On the other hand, the overly low foundations of Hualian Primary School, which were actually a leftover from the previous building on the site, resulted in paper tubes being damaged due to capillary action. Alternatives to concrete slabs include heavy components or boxes filled with sand, gravel or rubble. Furthermore, anchoring the building to the ground by means of ground screws or piles can save a lot of work and material and may increase the sustainability of the structure because it hardly touches the ground. Concrete beams or feet placed on the ground are a solution for smaller structures. More temporary buildings can be anchored to the ground with pegs, ropes or by covering the structure with canvas. As paper structures by their nature are lightweight, the role of the foundation is dual: to keep the structure in its place against the wind loads and the forces caused by things such as earthquakes and to protect the cardboard structure against moisture from the ground or surface water.

§ 4.4.6 Impregnation

Another challenging aspect of working with paper structures is the method used to impregnate the various components. As mentioned above, paper is vulnerable to water and moisture. As a hygroscopic material, paper can absorb water from the humidity in the air. Direct contact with water affects the bonds between cellulose fibres. In the process of hydrolysis, cellulose fibres are loosened up and paper turns into pulp. Therefore, since architects first began to use paper as a structural material, different methods have been used to impregnate the material. The position of the paper elements and components in the building plays an important role. It is advisable to place structural elements made of paper inside the building, so they can be protected from the elements by the enveloping structure that is the building.

The optimal moisture content of paper is between 5% and 7%. When the moisture content reaches 13%, the strength of the material is dramatically reduced. At a relative humidity level of 60%, the material's moisture content rises to 9.5%. At a relative humidity level of 90%, the material's moisture content increases to 15.8%, and the strength of the paper is reduced by one-third. The strength of paper is affected by differences in both temperature and humidity levels.

When working with building components like walls or roof panels which are made of paper elements, it is important to protect them from being damaged by moisture transported through the material. The transfer of moisture caused by differences

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in temperature inside and outside the building may cause condensation within the envelope. Therefore, a vapour barrier should be applied inside the building, while a water-resistant barrier should be installed outside. The most critical parts are cut edges and drilled holes. They must be treated particularly carefully with an additional layer of impregnator or special products that will protect them from moisture.

Another issue that must be addressed is ensuring that the paper and cardboard used are fireproof. Products like corrugated cardboard or honeycomb panels are composed of relatively thin layers of paper. Therefore, they are flammable, and a fire retardant must be applied to their surface. However, when a solid board or paper tubes are subjected to flames, a layer of carbon will form that will protect the underlying material from burning.

The impregnator applied to the paper elements should also protect them from other threats like UV, fungus, micro-organisms and rodents.

There are several different ways to impregnate paper products:

1. **Coating** – a layer of coating is applied to the product after manufacturing in the factory or on the building site. The coating can be applied by soaking, hot-pressing, thermo-fusing, spraying or painting the elements with a repellent. The coating can be natural, bio-based or artificial. Commonly used repellents include bio-polymers, resins, melamine-formaldehyde, urea-formaldehyde, GRP, sulphur polyurethane, polyethylene, gums, sprayed concrete, fibreglass, acrylic varnish, paraffin, wax, boiled linseed oil, copal varnish, polyurethane paints, resin-based paints and sprayed plastics. The coating process makes recycling more difficult since the repellent sinks deep into the structure of the material.

2. **Laminating** – lamination allows paper products to be combined with other materials, such as aluminium sheets, films, PVC foils, polyethylene foils, water barrier foils and polyurethane foam. It results in waterproof paper and creates a sandwich composition. The recyclability of the sandwich depends on the adhesive and covering material used.

3. **Impregnation of the mass** of the material, when substances are added to the pulp during the production process. This method affects the strength of the material. Depending on what type of repellent is used, recyclability may be restricted.

4. **Covering** the paper with another type of material, such as shrinking sleeves, canvas or fire- and waterproof paper.

Making paper water-resistant reduces its potential for recycling. It can be assumed that the heavier and more durable the impregnator, the less likely the product is to be recycled. However, products such as paper tubes may be recycled once their outer protective skin has been delaminated.

The chemical and paper industries are currently developing more new solutions for the impregnation of paper products. As this dissertation focuses on paper as a building material from an architectural and structural point of view, and particularly focuses on the details of the structure, it will not describe impregnation-related aspects in great detail. Although some information on the various impregnation methods is provided, they should be more thoroughly investigated by researchers and scientists specialising in chemistry and the production of paper.

§ 4.4.7 Processes of design, research and construction

Due to the legal issues inherent in the use of paper as a building material, the process of designing, researching and developing paper architecture must be conducted carefully. Fundamental technical research on the technology of paper and cardboard production and the design of a suitable structural system all have to be undertaken simultaneously. [13] During the design stage, when developing a new type of structure or structural details such as connections, a 1:1 scale mock-up of the building or a part thereof may be vital and useful. Prototyping is easy and extremely helpful. Furthermore, it is vital that the condition of the construction site be thought through. For example, if there is a risk of rain while construction is ongoing, the building site, or parts of the building, must be temporarily covered. Affordable transportation of the components and the distance between the manufacturing factory and the building site are important factors from a project profitability point of view. The high costs of prototype building have to be taken into account. Therefore, right from the start of the design and development process, architects should consider using elements previously produced by the paper industry and create a strategy for the further implementation of paper based materials to be used in architecture. Turning the paper industry onto paper architecture could be beneficial for the sake of material and knowledge support. The paper industry is a fast-growing branch. Therefore, investments in new and innovative ideas can be put to good use by researchers, designers and the industry. The key task is to promote proper communication between the paper-making and building industries and finding a niche market to compensate for the investment in facilities to make it commercially viable. Although it seems likely that the demand for small amounts of paper products with high quality requirements will only appeal to a few cardboard manufacturers.

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