6 Paper domes and shelters. Prototypes

Whatever you can imagine, you can also build!

Buckminster Fuller – motto of Bucky Lab course at TU Delft [1]

§ 6.1 Introduction

This part of the dissertation is dedicated to the practical approach to cardboard as a building material through prototyping. Taking a practical approach here means conducting research by design and prototyping architectural structures in which paper and its derivatives are used as the main structural material. The theoretical research and knowledge presented in the previous chapters of the dissertation will be now used as input.

The research by design and the realised prototypes will guide us to the solution that answers the question to what extent cardboard can be used as a suitable building material for emergency architecture.

The research and development of cardboard architecture used as input for this dissertation were derived from research previously conducted at TU Delft's Faculty of Architecture. The Cardboard in Architecture research group, which was set up in the department of Building Technology in 2003 and ceased to exist in 2008 due to the great fire that destroyed the building of TU Delft's Faculty of Architecture (13 May 2008), made a great contribution to this research. The fundamental and technical research was included in the previous chapters. The designs and development of products in the form of prototypes of cardboard structures are presented in this chapter.

TOC

§ 6.1.1 Previous research done at TU Delft

TU Delft's Faculty of Architecture has a long history of design and research on the application of paper and cardboard in architecture and their implementation in the form of the prototypes. In the year 1976 Chiel van der Stelt, Hans Mesem and Wim Kahman designed and built a prototype for a temporary house as part of their graduation project (see Fig. 6.1.). In 2002, Taco van Iersel, a member of the Cardboard in Architecture research group, developed a wall built from cardboard boxes as part of his graduation project (see Fig. 6.2.) In the same year Monique Verhoef designed and researched a cardboard structure as part of her graduation project. One year later, Pim Marsman and Jop van Buchem drew up a proposal for the new Stylos Bookshop which originated from a collaborative partnership between the Blob-architecture and Building with Cardboard laboratories. Joop van Buchem in his graduation project from 2004 proposed a parasite structure that was designed to be made out of cardboard.

Researchers from the Cardboard in Architecture group, in association with students of the university's Architecture and Building Technology departments, constructed a cardboard pavilion (see Fig. 6.4). The pavilion was presented at a two-day international symposium on paper and cardboard in architecture held in January 2006. Before the Cardboard in Architecture research group ceased to exist in 2008, the team realised several projects. Taco van Iersel developed his graduation project, called the Taco Wall, designed a preformed cardboard cable duct, and designed and built the Multished pavilion for a paper-recycling company in Duiven (see Fig. 6.3). Prof. Fons Verheijen designed The Wall, a sound barrier alongside the A2 motorway in which paper tubes are employed as a temporary sound barrier. The wall remained in situ for 1.5 years before being partly opened to provide some ventilation for the building behind the wall. In 2007, Prof. Verheijen and his students at TU Delft created the Transition House, a simple shelter composed of paper honeycomb panels covered by plastic canvas (see Fig 6.5). [2, 3]


FIGURE 6.1 Temporary cardboard house 1976


FIGURE 6.2 Taco Wall


FIGURE 6.3 Multished, 2002

FIGURE 6.4 Cardboard pavilion, 2006

FIGURE 6.5 Transition House 2007

More recently, research on paper in architecture was conducted by Casper Van der Meer, who defended his Master's thesis (entitled Developing the W-House) at TU Delft's Faculty of Industrial Design Engineering in 2013. Van der Meer's research included material tests he had conducted and the prototype of Wikkel House he had built with the Fiction Factory (for more information on this project, see Section 4.2.15).

Another TU Delft Master's student, Jan Portheine, built several prototypes of corrugated cardboard wall connections, which he presented in his dissertation written at the Faculty of Architecture, entitled Cardboard as a Construction Material for Beach Houses (see Figs. 6.6 - 6.8). Since 2015, Portheine and his colleague Wout Kommer have produced Kartent, cardboard festival tents that can be 100% recycled after being used. [4, 5]

FIGURE 6.6 Wall connection type A by Jan Portheine, 2015

FIGURE 6.7 Wall connection type B by Jan Portheine, 2015

FIGURE 6.8 Wall connection type C by Jan Portheine, 2015

§ 6.1.2 Research conducted by the author – general description

The author's own practical research in the form of research by design and prototyping and material tests on paper and cardboard as a building material started in 2009 at Wroclaw University of Science and Technology's Faculty of Architecture. In the years 2009-2012, he carried out the Paper as a Building Material research project, an examination of the potential of paper and cardboard in architecture, in association with scientific organisations affiliated with WUST and Lodz University of Technology's Institute of Paper-Making in Poland. The project involved the Bez(do)Mnie exhibition at the Wroclaw Contemporary Museum, as well as research on water- and fireproofing and the realisation of several projects featuring furniture and pavilions (see also Chapter 5: Domains of Paper Architecture). In 2013, the author of this dissertation, then an international researcher at Shigeru Ban Studio at Kyoto University of Art and Design, contributed to the preparation for the Miao Miao Paper Nursery School project. The project was carried out by Shigeru Ban Architects and Shigeru Ban's students and research students. The school was built during November 2013 and March 2014. The author of this dissertation took part in the first stage of construction, when the paper tube structure was erected. Together with other colleagues and members of the Voluntary Architects' Network he worked on site in the city of Ya'an in China in November and December 2013 (see more about the project in Section 4.3.14: Miao Miao Paper Nursery School). In 2015, he built the Exhibition Pavilion of Wroclaw University of Science and Technology, which employed paper tubes as a part of a hybrid timber/cardboard structure, together with students from WUST and TU Delft (see also section 4.3.16 Wroclaw University of Science and Technology 70th Anniversary Pavilion).

In 2012, 2014 and 2015, over a dozen prototypes were designed and built by students of TU Delft, supervised by the author of this dissertation (see Fig. 1.1). The projects carried out as part of the Bucky Lab course that is part of the Architectural Engineering and Building Technology tracks at TU Delft's Faculty of Architecture and the Built Environment were a series of prototypes that allowed the author of this dissertation to examine more closely different structural, geometrical and material solutions used in paper architecture. It was the last series of cardboard prototypes supervised by Prof. Mick Eekhout before he retired from TU Delft in March 2015. In 2016 the author's most recent project, an emergency cardboard shelter called TECH 03, was executed in the city of Wroclaw. The project was the result of previous research conducted by the author and was built in cooperation with Wroclaw University of Science and Technology and TU Delft.

§ 6.1.3 Projects and prototypes

The following section is devoted to practical research that encompasses design by research and prototyping. The projects presented here will be described and analysed in terms of geometry, structure, size, applied paper products of the packaging industry, the composition of the materials, connections between the elements and the components, possible production techniques and implementation. Furthermore, the potential for further development and application of the projects or parts thereof will be discussed as recommendations for further research.

The projects and prototypes were realised within the scope of Bucky Lab, a first-year Master's course that is part of the Architectural Engineering and Building Technology tracks taught at TU Delft's Faculty of Architecture and the Built Environment. The Bucky Lab is a block of courses supervised by Dr Marcel Bilow. It consists of Bucky Lab Design, where students design their project from the first sketches up to shop drawing; Bucky Lab Production Techniques, where the projects are built in the form of prototypes, either to scale or at a smaller scale; Computer Aided Design and Modelling; Structural Mechanics and Material Science.

§ 6.2 Cardboard shelter and dome prototypes

The following projects and prototypes represent the wide variety of domes and shelters that are made out of paper products and can be used as emergency shelters. The products incorporated into the projects were paper tubes, honeycomb panels, corrugated cardboard, paper board and L- and U-shapes made of paperboard. These products are mass produced by the global paper-making industry, which means they can be purchased at a low price almost anywhere. More information about the products and their properties can be found in Chapter 2. In addition to focusing on low-cost products, the students were instructed to design buildings that were easy to construct, store and transport and featured building elements and components that were so easy to combine that the structures should be able to be built even by non-professional construction workers. Another requirement was the possibility of organising the structures in groups or clusters so they could form bigger constellations designed to serve groups of people in need of large-scale accommodation.

The projects had to fall into the medium-sized category, which meant that their complexity level should be sufficiently low that engineering consultancy companies or contractors need not be hired to build them. Because the projects had to be medium-sized, their dimensions could not exceed 5mx5mx5m. However, the structures were allowed to cover a bigger area when clustered. The students did not have to focus on impregnation of the material, but some groups did consider this issue as part of their projects. Each project was first worked out in detail. At the same time the students consulted the author of this dissertation and dr Bilow. Then each design group or individual student prepared shop drawings, and lists of materials. During the design process, prototypes of parts of the structures often had to be executed in different scales, from 1:50 up to 1:1, in order to solve structural, technical or aesthetical problems. The prototypes were then constructed during the two building weeks (see Fig.6.9). Most of the projects were realised in 1:1 scale and presented at an exhibitions at TU Delft (see Fig. 6.10). Each project took about five months to complete. The final documents about the projects, i.e. the reports describing all the projects, were the source of the information and figures presented in the following section.

FIGURE 6.9 Workshop with Bucky Lab students at TU Delft, 2014

FIGURE 6.10 Exhibition of the prototypes produced by Bucky Lab students at TU Delft, 2014

§ 6.2.1 Cardboard Pop-Up Dome

Type of structure: folded plate structure
Realisation: January 2013
Location: TU Delft
Authors: Dwayne van Halewijn, Leon Zondervan
Design supervision: Jerzy Latka, Peter van Swieten
Prototyping supervision: Marcel Bilow, Jerzy Latka

The pop-up dome was a lightweight transportable and foldable cardboard structure. It was designed to be a shelter for different kinds of uses. The dome could be used as a shelter in refugee camps or places where natural disasters had struck, or alternatively, it could be used at festivals, fairs, etc. The dome had a folded-plate structure based on origami folding. The prototype was made from five layers of 7mm corrugated cardboard sheets, connected with glass-fibre-reinforced tape. The dome was 2.5m high and 4.5m in diameter (see Figs. 6.15 and 6.16). Once it was folded down, its dimensions were 2m by 0.5m. It weighed less than 50 kg, which meant it could be lifted by two persons. The structure was based on the 'Yoshimura pattern' from origami folding, also known as a 'diamond pattern'. The Yoshimura pattern, along with the diagonal pattern and the Miura fold, is one of the most interesting origami patterns from an architectural and structural point of view. The patterns provide three-dimensional forms with structural stability and can be modified and combined with each other. The Yoshimura pattern is named after the Japanese scientist Yoshimura, who noticed that the behaviour of a cylinder subjected to axial force follows the folds in a specific pattern, which is similar to a diamond (see Fig. 6.11). [6]

FIGURE 6.11 Yoshimura pattern on a cylinder [6]

The pattern consists of rhombuses, which are divided into triangles. The lines that are at the borders of each rhombus must be folded as mountains, and the lines that go across the rhombus must be folded as valleys.

The cardboard pop-up dome consisted of eight large triangles connected to each other sideways. Each of the triangles could be divided into fifteen rhombuses or thirty smaller triangles (see Fig. 6.12). By rotating the structure by approximately 100 degrees and by simultaneously lifting the octagonal roof panel, users were able to fold a small package into a full-size dome. All the walls (eight triangles) expanded when the structure was rotated and lifted vertically. With the help of five persons, the dome could be unfolded within two minutes (see Fig. 6.14).

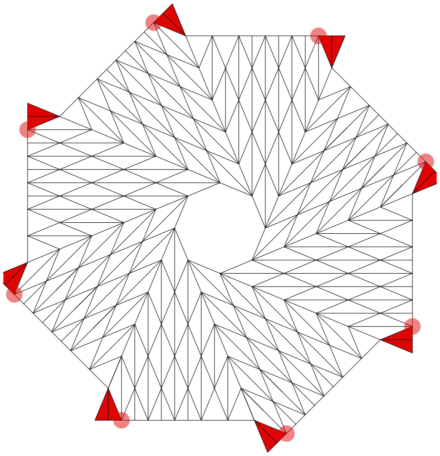


FIGURE 6.12 Fold pattern for the dome

FIGURE 6.13 Prototype of sloping hinges

The corrugated cardboard triangles were connected to each other with reinforced translucent duct tape. The basic problem was the thickness of the panel, which was hard to predict at this phase of the design. When a triangles was folded in, the thickness of this panels was cascading. Therefore, the hinges had to connect two cascading edges. The solution the students researched was a sloping hinge with solid cardboard beams and a 10mm gap between the big triangles in order to obtain a linear hinge (see Fig. 6.13).

The roof element was an octagonal plate added to the top of the dome. Piano hinges were used to connect the roof plate, to prevent the tape connections from tearing. The hinges were bolted to the cardboard, and by use of big washers forces were distributed over a bigger surface to prevent tearing of the material.

The project was developed in three stages. In the first stage, when the primary design was drawn up, a 1:3 scale model was built in order to check the stability of the structure. In the second phase, the model was rebuilt and the plate connections were worked out in greater detail. Later one-eighth of the dome was built with a scale of 1:1. The third stage was a complete 1:1 prototype.

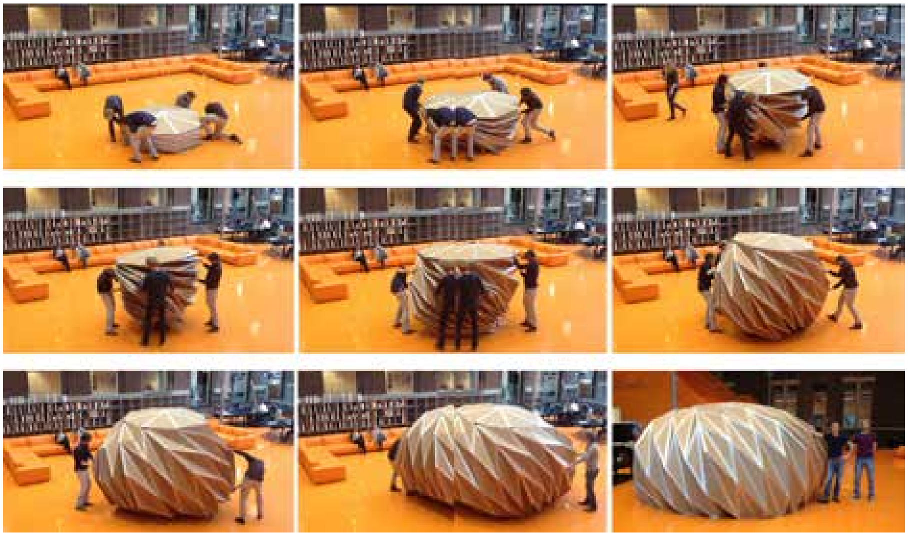


FIGURE 6.14 Opening the dome

FIGURE 6.15 1:1 scale prototype of the unfolded dome

FIGURE 6.16 Interior of the dome

Evaluation

The idea and realisation of using a folded plate structure to create a pop-up dome were successful. The most difficult part was finding a proper solution for hinges. The sloping hinges allowed the plates to be connected with each other while the thickness of the panels changed along the side of panels. The use of reinforced duct tape and piano hinges made the structure sufficiently strong and ensured that the various parts of the structure were well connected. The structure was built as a prototype in 1:1 scale and proved stable. However, the material used, five-layered corrugated cardboard, seemed to be too wiggly. If strengthened, the structure could be used as a formwork for further reinforcement with, say, a thin layer of concrete or epoxy poured onto the outer surface. The corrugated cardboard could be replaced with honeycomb panels, which would be thicker and stiffer but also lighter. Sandwich panels made of cardboard and some insulating material, like Styrofoam or polyurethane, would be a promising solution. The other option would be sandwich panels with aluminium sheeting on both sides. Yet the dome would not be used for emergency situations but rather for profitable events like festivals, exhibitions or trade fairs. The most valuable aspect of the project was the foldable mechanism that would ease storage and transportation and allow the structure to be erected quickly in an emergency situation. In general, origami and its folding techniques are a rich source of inspiration for architects, and should be investigated in the future as a solution for usable emergency structures. Although the prototype seemed to work correctly, issues such as windows, ventilation or openable doors would arise in reality. Ventilation openings were created in the octagonal roof plate, but the doorway rendered the structure more unstable. The greatest qualities of the project were its bold and unique appearance and beauty, as well as the ease with which it could be transported. The pop-up dome can be erected as a standalone or in a group. Further research should consider its connection to the ground (slab or anchors) and thermal insulation.

§ 6.2.2 6.2.2. SCOLP (Structural Connection of Laminated Paperboard)

Type of structure: shell structure (geodesic dome)
Realisation: January 2013
Location: TU Delft
Authors: Patricia Knaap, Bram Teeuwen
Design supervision: Jerzy Latka, Peter van Swieten
Prototyping supervision: Marcel Bilow, Jerzy Latka

TOC

The idea behind SCOLP was to design and build a dome that consisted entirely of cardboard elements, including the connections.

Several types of geodesic domes with frequencies ranging from 1V to 6V were considered. In the end, a 2V-icosahedron-based dome was selected for prototyping. All icosahedron geodesic domes have six 5-way connections. The most basic shape, a 1-frequency (1v) icosahedron dome, consists of 20 equilateral triangles. A 1v dome has just one strut between two neighbouring 5-way connections. A 2v icosahedron dome has two struts between the 5-way connections. As a result, the basic triangular form 1v is divided into two. Higher-frequency domes have more subdivisions of the basic shape (1v) which also results in more connections and struts (see Fig. 6.17). Moreover, an even-frequency dome has a dividing line exactly across the centre of a sphere, while odd-frequency spheres have to be divided slightly above or below the centre line. This is why 3v domes do not have a flat base and come in three-eighths or five-eighths versions. In this case, a sphere was cut in half and the resulting dome was placed on the ground and all the anchor nodes were positioned in one plane. A 2V icosahedron dome has three types of connections: ten 4-way connections which are at the bottom of the dome, where they serve as anchor points; six 5-way connections, four of which are located in the middle of the dome and one at the top; and ten 6-way connections. The 5- and 6-way connections are alternated. In a 2V dome the struts only come in two different lengths, so there were thirty-five ‘A’-type tubes measuring 1.70m and thirty ‘B’-type tubs measuring 1.50m. The tubes had an internal diameter of 60mm and the walls were 5mm thick. The radius of the dome was 2.75m (see Fig.6.18).

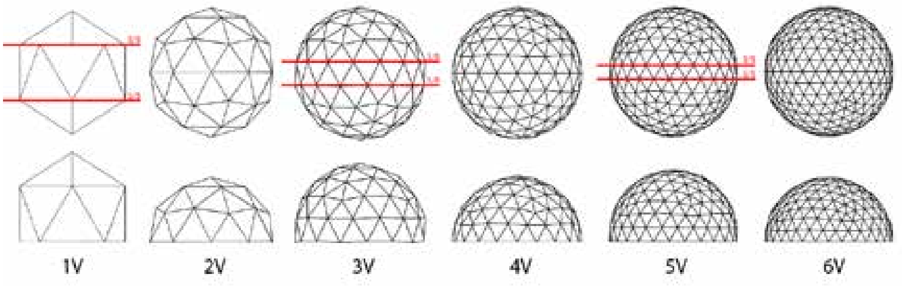


FIGURE 6.17 Geodesic sphere and dome structures with different frequencies

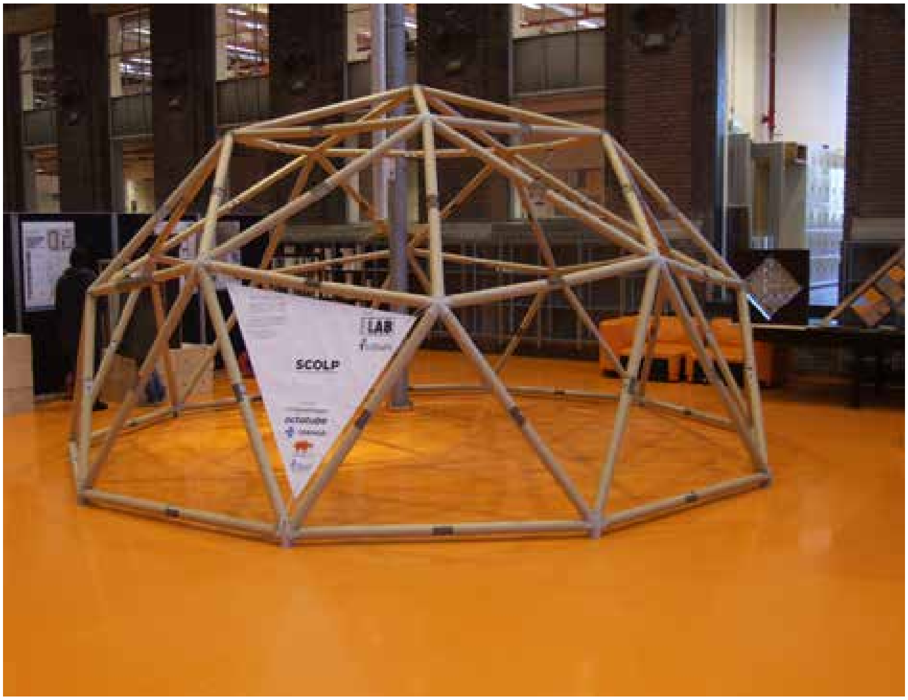
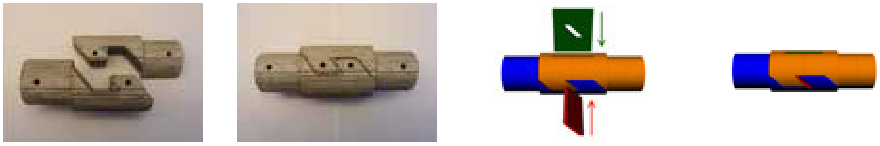


FIGURE 6.18 1:1 scale prototype of SCOLP

As the idea behind the project was to build a dome entirely out of cardboard, including the tubes and nodes, the connections between the paper tubes also had to be made of cardboard.

A dome was constructed using hollow paper tubes and massive laminated connections made of fully laminated paperboard. Connecting the dome rods in the 4-, 5- and 6-way connections was problematic, because all the parts had to be connected at the same time. Therefore, the connectors were moved to the middle of the rods. In other words, the 4-, 5- and 6-way connections were designed as solid and stiff connections in the form of a starfish, but the paper tubes were cut into halves and connected at the halfway point by means of specially designed locking cardboard connectors (see Fig. 6.19). The connectors in the middle of the rods consisted of two parts, each of which had a hook that perfectly fit into the part. The starfish-shaped connectors were connected to the paper tubes by rotation parallel to the surface of the dome (see Figs. 6.20 and 6.21). Both the starfish-shaped connectors and the hook-shaped connectors were prefabricated out of laser-cut and laminated layers of 3mm thick paperboard. The midway connectors, having been inserted into each other, were locked with cardboard wedges.



1 *2* *3* *4*

FIGURE 6.19 Laminated cmidway ardboard hook-like connector; **1** seperated; **2** connected; **3** locking with cardboard wedges; **4** locked midway connector

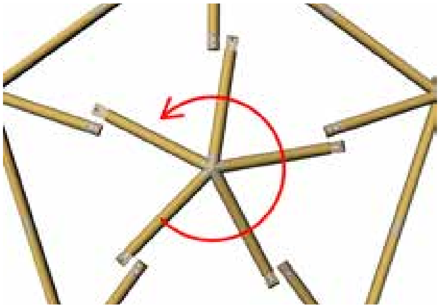


FIGURE 6.20 Starfish-shaped connection and method of assembling the dome elements

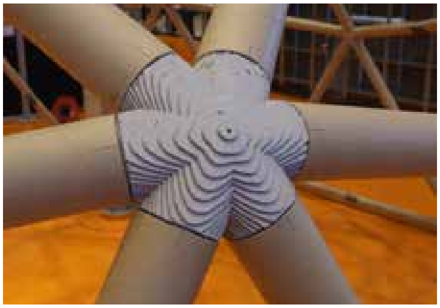


FIGURE 6.21 Starfish-shaped connection

Evaluation

The SCOLP project showed that it was possible to produce a structure entirely out of cardboard. However, the production of laser-cut, laminated and then sanded nodes proved expensive and time-consuming. If a bigger dome had to be erected, even thicker nodes would be required. The maximum thickness of the paperboard was 5mm due to the production and drying process. The idea of midway connections made it easy to erect the dome, although there was still a stability issue to be solved by means of a rigid cylindrical sliding tube. If the connections were made to coincide with the 4-, 5- and 6-way starfish-shaped nodes, both design and production would be much more complicated and the erection process would require more people in order to fit all the elements together at the same time. When covered with canvas, SCOLP could serve as a primary shelter. When scaled up, it could be used as a gathering place or social room for communities. However, the amount of work and complexity involved in the production of the nodes suggests that it might be better to use connectors made of wood or steel. The dome could be transported in the form of prefabricated star-shaped components and could be erected on site. As the midway connectors were easily combined, the construction process could be accomplished by non-professionals. However, if the nodes were made of cardboard, as in this project, said nodes (particularly the anchor nodes) would require impregnation to prevent damage caused by water.

TOC

§ 6.2.3 Curved-fold dome

Type of structure: Shell structure (geodesic dome)
Realisation: January 2013
Location: TU Delft
Authors: Dennis IJsselstijn, Pedro Calle
Design supervision: Jerzy Latka, Peter van Swieten
Prototyping supervision: Marcel Bilow, Jerzy Latka

This curved-fold dome is three-eighths of a 3V-frequency geodesic dome based on an icosahedron shape. The project was mostly focused on one element: the strut, which was produced in series that ended up making up the entire structure. The struts thus produced were folded from a single sheet of corrugated cardboard (see Figs. 6.23 and 6.24). The curved folding pattern led to a strut curved in two directions, so that it would satisfy the compression and tension strength requirements. The struts were made of five-layered corrugated cardboard recycled by the students from bicycle boxes.

FIGURE 6.22 Curved Fold Dome, 1:1 scale prototype

The dome was 7 metres in diameter. It consisted of three types of struts: 30 x Type A with a length of 1.22m, 40 x Type B with a length of 1.41m and 50 x Type C with a length of 1.44m. The total volume of the unfolded dome was 0.9 and it weighed 54 kg (see Fig.3.22).

The dome had 46 joint members in the form of pentagons and hexagons. They were made up of four laminated layers of corrugated cardboard, which overlapped with the ends of struts. The joints and struts were held together with zip ties (see Figs. 6.25 – 6.27). The zip ties worked in two ways. On the one hand, they kept the cardboard elements together. On the other hand, they provided extra shear resistance between the cardboard layers.

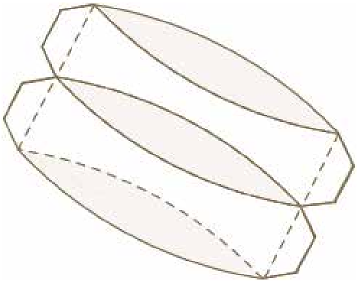


FIGURE 6.23 Folding pattern of the struts

FIGURE 6.24 Folded struts

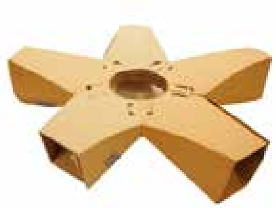


FIGURE 6.25 Joint members between the dome's struts

FIGURE 6.26 Scaled model of the joints between the struts

FIGURE 6.27 Joint members connected with struts by zip-ties

The dome was set on footers composed of folded cardboard elements. Fifteen footers held the bottom row of hexagons with zip-ties. The footers were hollow on the inside, so it was possible to fill them with something heavy for improved stability (see Figs. 6.28 and 6.29).

Structural analysis showed that 4cm thick joints could hold the dead weight and wind loads (see Figs. 6.30 and 6.31).

FIGURE 6.28 Footers being created during the production of the prototype

FIGURE 6.29 Detail of locking mechanism of footer

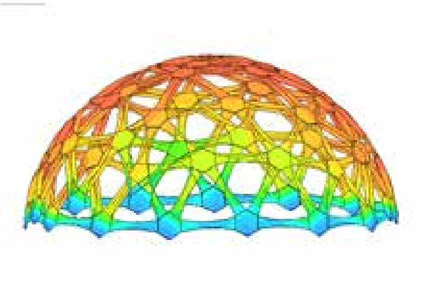


FIGURE 6.30 Structural stability analysis performed in Diana software, front view

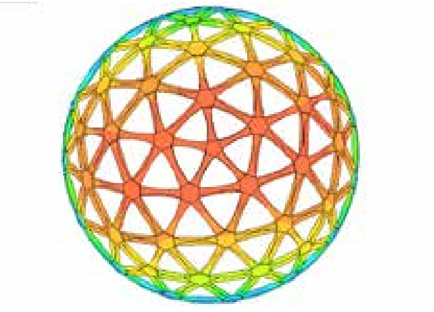


FIGURE 6.31 Structural stability analysis performed in Diana software, top view

Evaluation

This project showed how strong cardboard is if it is used in a shell structure. The curved folding method involving struts provided the material with extra strength. Five-layered corrugated board, 7mm thick, folded into struts, held the entire structure of the dome, which measured seven metres in diameter. The 5-way and 6-way connections between the struts were produced as laminated cardboard elements connected with the struts by means of zip ties. Although the material itself was strong enough, the use of zip ties damaged the cardboard because it caused point forces. The connections needed some more work. Possibly another type of material should be used in the form of a sandwich, with, say, plywood. The dome could be covered with canvas. For this reason, a connection between the structure and the canvas should be devised. The connection with the canvas could be installed in the hollow parts of the cardboard joint members. The main problem with using this structure in an emergency situation would be the doorway. Creating a door would result in reduced stability. Clearly, this is something that requires more consideration. As the struts are folded from flat plates, they can be easily stored and transported in large numbers.

TOC

§ 6.2.4 Auto-lock box dome

Type of structure: shell structure – dome
Realisation: January 2013
Location: TU Delft
Authors: Hans Haagen, Xindroe Volmer
Design supervision: Jerzy Latka, Peter van Swieten
Prototyping supervision: Marcel Bilow, Jerzy Latka

The main goal the creators of the auto-lock box dome sought to achieve was simplicity, not only in the construction of the dome, but also in its assembly and disassembly. Furthermore, they sought to make the dome foldable into small packages, and therefore easily transported. The idea behind the primary structural element was an auto-lock box. An auto-lock box is flattened when pressed in one direction and automatically assumes the shape of a box when pressed in another direction (see Fig. 6.32). In this project, the flaps of the box were designed to interlock at a particular point when the box was fully opened. Since some of the flaps were glued together, they forced the other flaps to act simultaneously (see Figs. 6.33 and 6.34). The cube-shaped element consisted of two auto-lock mechanisms on either side of the box. This solution enabled the creators to fold the box when forces were applied on the two opposite corners of the box. However, if the forces were applied to the two other corners, the box was pushed flat. To allow for the curvature of the dome, the basic elements were designed as tapered boxes. In order to achieve the curvature needed to construct a dome, the higher rows of boxes were smaller than the bottom ones.

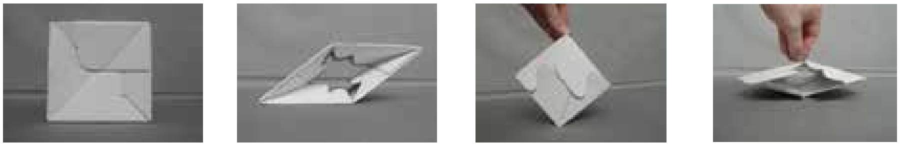


FIGURE 6.32 Folding mechanism of the auto-lock box

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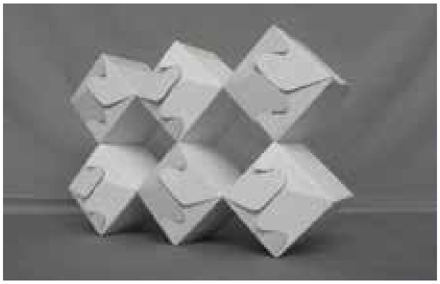

FIGURE 6.33 Folding mechanism of several auto-lock boxe, opened structure

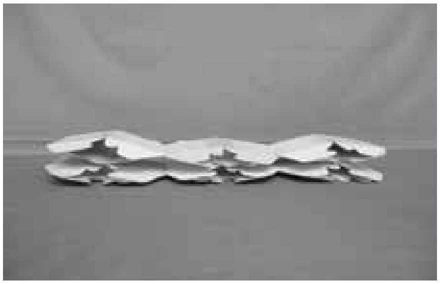

FIGURE 6.34 Folding mechanism of several auto-lock boxe, closed structure

In order to make the folded down dome easy to transport, the whole structure was divided into three main elements. The first element was the legs, which were all divided into two smaller parts. The length of each leg was approx. 4.5 metres, so they were separated into two parts with a length of two metres each. At the bottom of the dome was a tensile ring that prevented the legs from moving outwards. At the top there was a connection ring. The boxes were positioned at a 45-degree angle, so that top-down forces locked them into place and made them stronger. Because the legs were very thin at the bottom, the structure was likely to buckle. To prevent it from collapsing, a tooth-shaped tensile ring was designed to fit into the triangular gaps between the bottom boxes and connected to them by means of flaps.

Due to budget constraints, only one leg of the entire dome was prototyped. It consisted of 95 laser-cut and 26 hand-cut boxes. Thirteen different types of boxes were laser-cut from 1mm thick corrugated cardboard (see Figs. 6.35 and 6.36).

FIGURE 6.35 Visualisation of the whole auto-lock box dome

FIGURE 6.36 Prototype of one 'leg' of the dome

Evaluation

The structure of auto-lock dome shows a different approach to the use of cardboard elements in architectural structures. Although the prototype was not perfect and the boxes had to be manually opened and kept in position with special buttons added later, the idea of the smart and simple mechanism of auto-locking worked well. Such kinds of elements, flat when transported and fully formed after erection, can be used as cardboard bricks filled with polyurethane foam or some local material (such as mud) following erection. Further development should take into account the thickness and stiffness of the material and the connections between the boxes. Thicker cardboard is suggested and some parts, like the bottom (tensile) ring and its connection to the boxes, could be made from different material, i.e. wood. The idea of the folding and auto-locking structure could be applied to a simpler structure. The composition featuring boxes could be used as a prefabricated component of a wall composed of folding cardboard bricks. A component made of a series of interconnected boxes could be further developed, in a way similar to the Taco Wall (see also section 6.1.1) .

§ 6.2.5 Waffle Dome

Type of structure: Single-layered dome
Realisation: January 2015
Location: TU Delft
Authors: Sofie van Brunschot, Luis Lopez, Rutger Oor, Pamela Zhindon
Design supervision: Jerzy Latka,
Prototyping supervision: Marcel Bilow, Jerzy Latka

The concept of this project was a dome built from ribs interlocking in a waffle-like structure (see Fig. 6.37). The design goal was to create a cosy personal space for people in need. The ribs were positioned in the X- and Y-direction and were made to intersect at the halfway point. Therefore, the ribs had slots cut at the halfway point. The Y-directed ribs had cuts on the upper half, the X-directed ribs on the lower half (see Fig. 6.39). The dome was symmetrical, so in total there were sixteen ribs making up a dome. There were only ten types of ribs. Another eighteen ribs were needed for the flooring. Each of the ribs was composed of three layers of double-corrugated cardboard laminated with wood glue. Each layer of the cardboard was 6.4mm thick, so the total thickness of the ribs was 19.2mm. The dome was 3m high and had a span of 3.2m (see Fig. 6.40). The area of the Waffle Dome was approximately 9m^2. It weighed approx. 70 kg. There were two entrances. The dome could be clustered in bigger groups by connecting the entrance portals to each other (see Fig. 6.38).


FIGURE 6.37 Prototype of Waffle Dome


FIGURE 6.38 Rendering of clustered domes

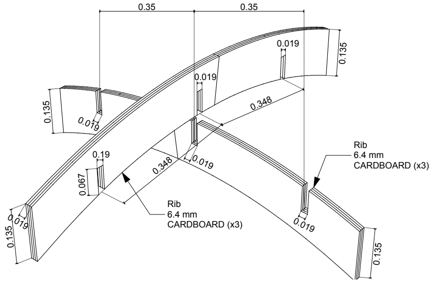

FIGURE 6.39 Prototype of Waffle Dome

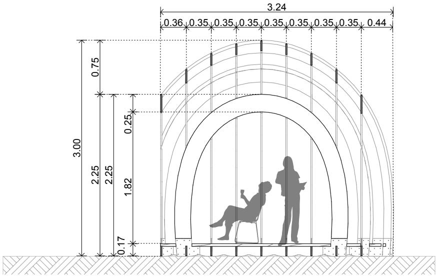

FIGURE 6.40 Rendering of clustered domes

The grid at the top of the dome could be covered by several types of materials in order to protect it from the elements and to create a layer of thermal insulation. Specially designed cardboard boxes that could be inserted into the grid and filled with thermal insulation material could make the structure more stable. However, the boxes had to be impregnated. The other option was to cover the dome with textile in such a way that it would create cushions between the ribs. These cushions or pockets could be filled with insulating material like wool, old newspapers, hay or grass. Covering the dome with translucent PVE (polyvinyl ether) fabric was a third option, and this is the one the students ended up choosing (see Fig. 6.41). Two possibilities were considered to improve the stability of the dome: cardboard L-shape profiles bolted to the corners of the dome grid, or tension cables applied diagonally between the ribs (see Fig. 6.42).

FIGURE 6.41 Composition of the structure and its cover

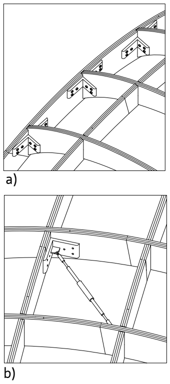

FIGURE 6.42 Concepts for stabilising the structure: a) with cardboard L-shapes; b) with tension cables

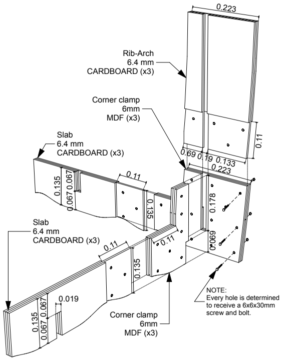

FIGURE 6.43 Connection between ribs and floor elements

The floor grid was made out of corrugated cardboard boards cut in a waved pattern at the bottom to allow water to pass through. The floor ribs were connected with the ribs that formed the dome by means of shoe-shaped wooden L-shaped joints, which were bolted to the floor and to the ribs of the dome. The ribs of the floor were covered with wooden boards (see Fig. 6.43).

The ribs of the dome could be transported as a flat package. However, since they were only 19.2mm thick, they were very wiggly, which made erection of the dome difficult. Yet once the structure was complete and all the ribs intersected, the dome had the expected level of stability. Although construction was simple and the number of elements was small, the process was harder than it should have been due to the thinness of the ribs. A few ribs actually broke during transportation and during the erection process. The estimated time of construction was 1 to 1.5 hours.

During the design and prototyping process, several mock-ups were constructed. After the students had completed the design and computation, a scale model (1:20) was built in order to check the overall look of the structure. Then a part of the structure was built in a 1:1 mock-up. This step allowed the students to check the rigidity of the rib connection and the desirable thickness of the ribs. Afterwards, a 1:5 scale model was made to check the stability of the whole structure. The last working model was a 1:1 scale mock-up of the wooden 'shoes' that connected the ribs of the dome to the ribs of the floor.

Evaluation

The Waffle Dome showed a phenomenon described by Shigeru Ban in the sentence: 'Good design can create strength from weakness'. It was almost Japanese or Chinese in that it connected slender and weak timber elements in such a way that they actually gained strength. Once it had been assembled, the Waffle Dome, which consisted of elements that were merely 19.2 mm thick, displayed surprising strength. This shows that even very fragile and weak elements can result in stable structures when combined. Nonetheless, this type of structure would be too complicated to assemble in an emergency situation, when a shelter must be constructed in very limited time. The ribs proved fragile during the transportation of the parts from the production hall to the exhibition area. It is clear that they should be reinforced by some additional material or by a layer of insulation material, e.g. resin. The interlocking mechanism worked well and did not need to be strengthened by bracing or by inserting any additional material into the grid. However, in real life, if the dome were to be placed outside, the forces caused by, say, wind might prove too strong for the structure. The ribs of the floor should be made of some water-resistant material or impregnated wood. The empty spaces between the ribs could be filled to give the structure better thermal insulation from the ground. The best thing about this design was the possibility of clustering the domes in bigger groups, so they could serve small groups or communities. Another good thing about the project was the process of developing the final shape and technical elements such as connections based on several mock-ups and scale models, assisted by computational design. This helped prevent mistakes and errors in the early stages of the design.

§ 6.2.6 BYOH (Build Your Own Home)

Type of structure: Folded plate structure
Realisation: January 2015
Location: TU Delft
Authors: Chris Borg Costanzi, Andrius Serapinas, Antonia Kalatha, Dorine van der Linden
Design supervision: Jerzy Latka,
Prototyping supervision: Marcel Bilow, Jerzy Latka

The authors' goal was to design an instantly deployable shelter that could be delivered at a certain place and be erected by unfolding a few parts within five minutes. To achieve this aim, the authors consulted examples of origami folding techniques. Their

TOC

research on origami techniques focused on the Miura fold and the Yoshimura pattern, as well as their variations and corresponding folded forms. The Miura fold consists of symmetric parallelograms forming a zizag configuration in two directions. The pattern can be open at two ends. The pattern was named after the Japanese scientist Miura, who used it to create a kinetic solar system in space. [6] For an explanation of the Yoshimura pattern, see the description of project 6.2.1 (Cardboard Pop-up Dome). The main difference between the two patterns is the direction of the folds. While the Yoshimura pattern consists of a diamond folding along the diagonals, with the diagonals being folded as valleys and the edges being folded as mountains, the Miura fold forms a tessellation of the surface by parallelograms. The students combined the two patterns in order to achieve a foldable shelter in the form of a hemisphere, with an open entrance. The Yoshimura pattern was used to create the main body of the shelter, while the Miura fold was used for the creation of the entrance. This resulted in a structure that was 185cm high, 390cm wide and 420cm long (see Fig. 6.48).

FIGURE 6.44 Miura fold

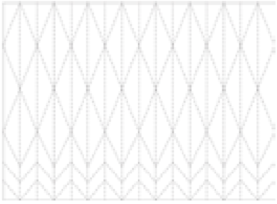

FIGURE 6.45 Combination of the Yoshimura and Miura patterns

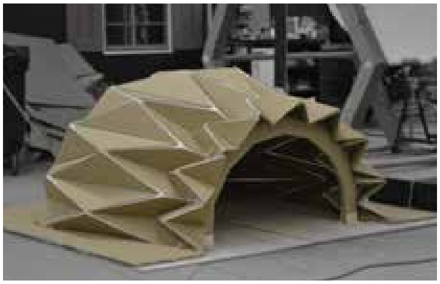

FIGURE 6.46 1:2 scale prototype of the BYOH shelter, front

FIGURE 6.47 1:2 scale prototype of the BYOH shelter, back

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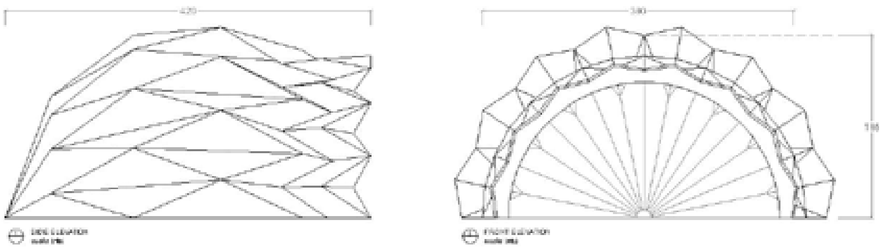


FIGURE 6.48 Dimensions of the original 1:1-scale structure

The pattern consisted of sixteen rows, each of which was composed of triangular or rhomboid panels. The panels consisted of three layers. The top and bottom were made of cardboard panels, while the cardboard in the middle had grooves that left some room for insulation material (see Fig. 6.49).

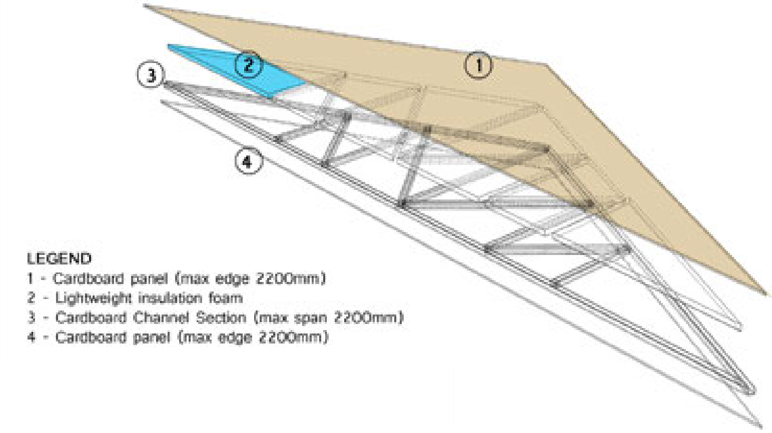


FIGURE 6.49 Composition of single plate

As origami is a folding technique involving very thin sheets of paper, the problems occurred at the very connections, where the material had to be thicker for strength and rigidity purposes. To deal with this, special hinges had to be developed to connect separate cardboard plates. A so-called 'living hinge' was developed for this purpose. A living hinge is a series of laser-cut lines of pre-determined length and spacing that connect the panels and allow cardboard, a non-flexible material, to bend with ease (see Figs. 6.50 and 6.51). The hinges were tested in 1:2 scale and they did their job well, but the high costs associated with laser-cutting made the hinges unusable in the final prototype. However, in a real-life situation, if the units were produced in series, living hinges would be a desirable solution as they are made from the same material as the plates. The idea of living hinges could be worked out in greater detail in future research projects involving folding cardboard structures. In this case, since the cost of the living hinge was prohibitive, another option had to be found. In the end, translucent duct tape, reinforced with fibres in both directions, was used to connect the cardboard plates, as an alternative to living hinges.

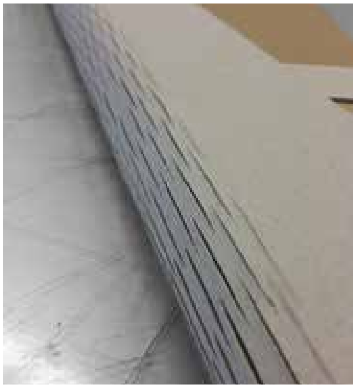


FIGURE 6.50 'Living hinge' folded


FIGURE 6.51 'Living hinge'


FIGURE 6.52 Reinforced translucent tape hinges

To create an entrance to the shelter, the origami folding pattern needed a structural element to support the doorway. An element in the form of an arch with triangles along the upper curve was incorporated. The triangles closed the structure and defined the shape of the origami structure, while at the same time providing greater stability by absorbing lateral wind forces. The arch was composed of ten layers of 6.4mm thick corrugated cardboard. The bottom parts of the arch were flanked with wooden plates that provided the laminated cardboard with stability and protection. There was a slot in the floor panel into which the entrance arch could be inserted. The arch was connected with the slot by bolts (see Fig. 6.53).

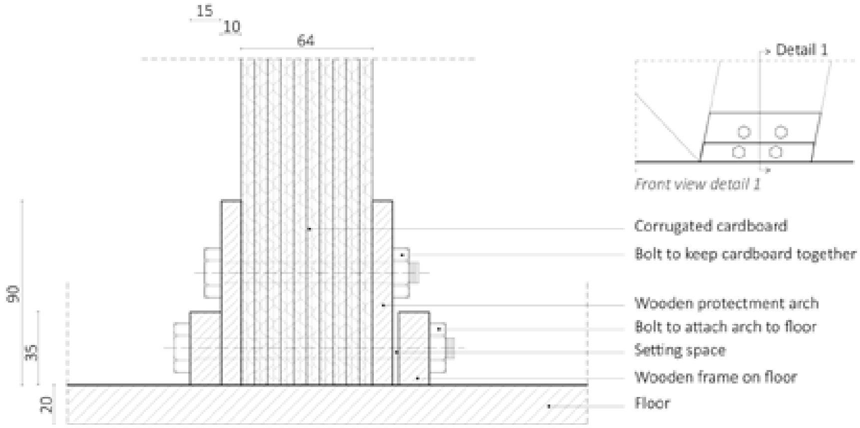


FIGURE 6.53 Composition of single plate

The connection between the origami pattern and the entrance arch along its curvature was achieved by means of elastic rope. The rope was attached to the floor after the structure was erected and opened. The floor consisted of two plywood plates and folded down under the whole structure while being transported. An additional honeycomb layer was glued to the top section of the floor panels in order to make the structure more stable. The elastic rope was also used in the back of the shelter in order to stabilise it into position.

FIGURE 6.54 Open structure with the entrance arch fitted to the floor panel

FIGURE 6.55 The structure folded down

A prototype of the BYOH was prepared in 1:2 scale. The panels were composed of two cross-laminated layers of corrugated cardboard instead of three layers with a cavity in between, as planned. The single units of BYOH could be clustered together into groups of three or even bigger complexes by means of a special corridor combined with arches (see Fig. 6.56).

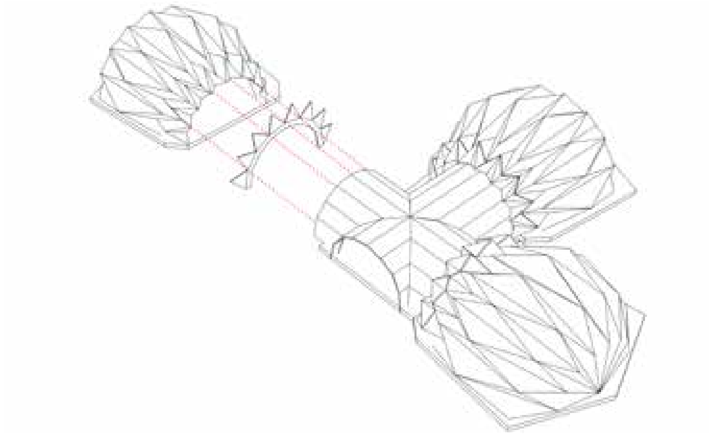


FIGURE 6.56 Possible arrangement of three shelters attached to each other by a special corridor

Evaluation

BYOH is a successful development of a shelter based on origami folding. The Miura fold and the Yoshimura pattern were combined to achieve a hemispherical space with a doorway that could be unfolded from a flat package. Further research should concern the closing of the doorway, the potential for thermal insulation and a stable connection between different elements: the floor panel, the structure itself and the doorway. BYOH is an excellent example of an instant shelter which, once set up, may be able to be reinforced in the future by pouring concrete on its outer surface. In this way the temporary shelter may be able to be upgraded to a permanent shelter, without anyone having to move out. The downside of both the living hinges and the duct-tape hinges is the thermal bridges which would occur on the whole surface of the shelter. In the original project, triangular plates were made out of three layers. The use of U-shaped cardboard elements as channels for thermal insulation material is an idea worth pursuing.

The BYOH project was awarded a prize in an international competition for emergency-housing proposals for refugees in the countries on the Mediterranean Sea, organised by the MOHA Research Center in 2016. [7]

§ 6.2.7 The Umbrella Shelter

Type of structure: Columns-and-beams rod structure
Realisation: January 2015
Location: TU Delft
Authors: Andreja Andrejevic, Li Yu Wai
Design supervision: Jerzy Latka,
Prototyping supervision: Marcel Bilow, Jerzy Latka

The Umbrella Shelter was a deployable, foldable shelter that became 3.6 times larger once unfolded. The umbrella mechanism was used twice, both at the top and at the bottom of the structure. The shelter was octagonal in plan, was 300cm high and 350cm wide and covered an area of 9m^2 when unfolded. When folded, it measured 360cm (height) by 178cm (width), with the area of 2.5m^2. When the structure was closed, the top of the roof structure slid downwards, while the bottom, which was the floor structure, moved upwards (see Fig. 6.57).

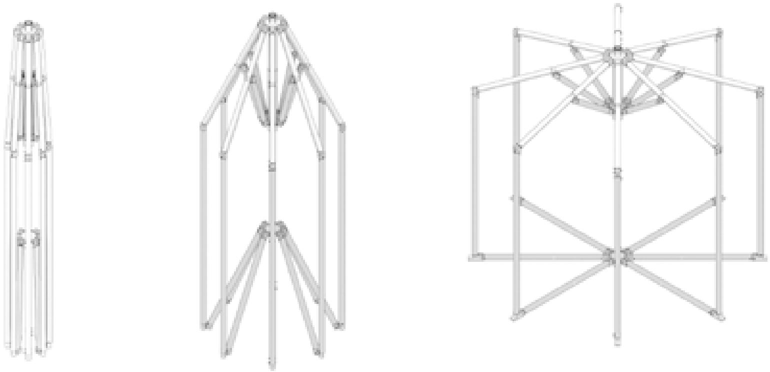


FIGURE 6.57 Folding mechanism of the Umbrella Shelter

The shelter consisted of two parts: the frame structure and the envelope (see Figs. 6.58 and 6.59). The frame structure was composed of paper tubes connected with wooden joints by means of bolts. Six different types of hinges were incorporated into the joints. The envelope came in two different versions: one for warmer climates and one for colder climates. In the envelope designed to be used in warm areas, honeycomb panels were used for the floor, while waterproof fabric was used for the walls and roof. The fabric was sewn together to form one whole, consisting of eight wall rectangles and roof triangles. The fabric was transported along with the structure. The fabric was connected to the paper tube structure by means of Velcro. In the envelope designed to be used in colder areas, the walls, roof and floor were combined into eight separate panels made out of honeycomb panels. In this case the honeycomb panels were installed after the structure had been unfolded. Some extra insulation material such as wool fibres, foam or cotton could be incorporated into the panel structure by adding it between the honeycomb cells. Both the fabric and the honeycomb panels were prefabricated in three different styles: one with a door, one with a window, and one in the form of plain wall (see Figs. 6.60 and 6.61).

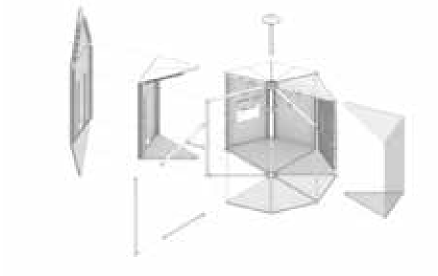


FIGURE 6.58 Exploded axonometric view of the Umbrella Shelter

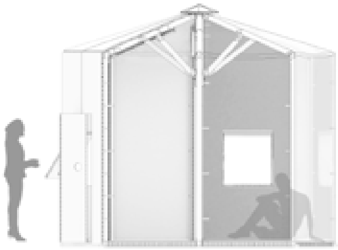


FIGURE 6.59 Section of the Umbrella Shelter

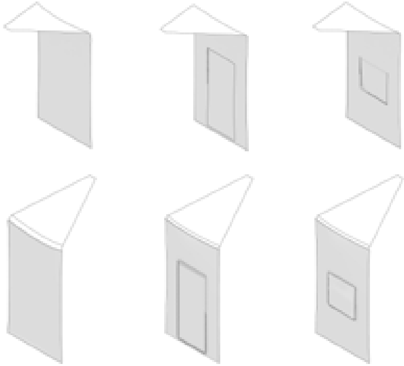


FIGURE 6.60 Type of covering made of fabric

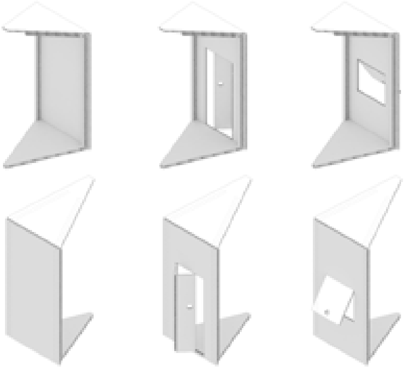


FIGURE 6.61 Type of covering made of honeycomb panels

There was a ventilation shaft at the core of the structure. The central tube, which held the structure of the roof, also served as the ventilation shaft (see Fig. 6.62 and 6.63). The central wooden ring connected with eight paper tubes held diagonally. When the shelter was unfolded, the ring was locked in position by a pin going through the central paper tube, in order to prevent it from sliding off the tube (see Fig. 6.65).

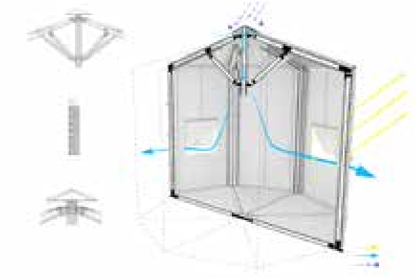


FIGURE 6.62 Ventilation method – inlet of fresh air

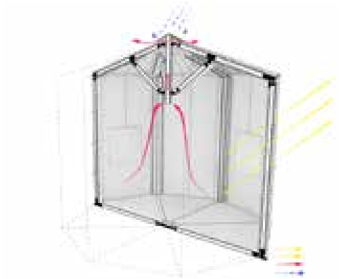


FIGURE 6.63 Ventilation method – outlet of exhaust air

FIGURE 6.64 1:1 scale prototype of the Umbrella Shelter

FIGURE 6.65 Details of the connections between the paper tubes

Evaluation

The Umbrella Shelter included a folding mechanism inspired by the mechanism of an umbrella. The greatest advantage of the project was the simplicity of the structure, which was based on paper tubes. Other pros were the fact that the process of unfolding the structure took very little time (just over one minute) and that the structure in folded form only took up very little space. The joints and connections between the paper tubes, made of laminated plywood, worked well. Prefabricated covering elements in the form of fabric or rigid insulated panels made of honeycomb allowed different arrangements of the space. The connection between the skin and the structure should be developed further in order to avoid gaps. Some of the wooden elements were too weak and broke during transportation, so the project will need improvement and further prototyping if this type of shelter is ever to be produced. The shelter with its octagonal space can be used not only as a shelter but also as an information centre, small shop or anything else that needs to be erected quickly and taken away at the end of the day. The honeycomb panels used for the walls and roof of the shelters intended for colder climates need more work, and should consist of sandwich panels, because the proposed solution (with only one layer of panels) was too thin to provide the required thermal insulation. This type of shelter is hard to cluster. They should act as single units deployed next to each other, rather than as bigger shelters for groups or families.

FIGURE 6.66 1:1 scale prototype of the Umbrella Shelter

FIGURE 6.67 Details of the connections between the paper tubes

§ 6.2.8 The HEX Shelter

Type of structure: Shield wall and beam structure
Realisation: January 2015
Location: TU Delft
Authors: Bayu Prayudhi, Priyanka Ganatra, Wan Yun Huang
Design supervision: Jerzy Latka,
Prototyping supervision: Marcel Bilow, Jerzy Latka

The main idea behind this project was to develop an easily deployable shelter that could be completely prefabricated, easily stored and transported, and unfolded in little time. The design was inspired by Japanese capsule hotels, and so called for the creation of small single-person units. However, the modular micro-dwelling would not necessarily have to serve as a sleeping unit. It could also be used as a micro-shop, storage shed, study space, etc. Thus the dimensions of the unit should fit the human scale (see Fig. 6.68).

FIGURE 6.68 Visualisation of a group arrangement of HEX Shelters

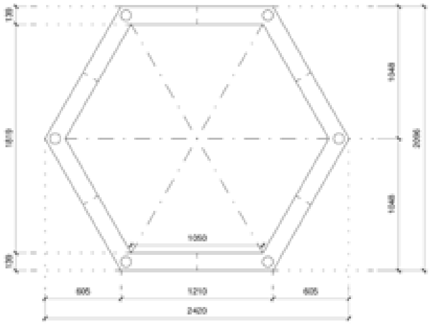


FIGURE 6.69 Dimensions of the cardboard hexagonal frame

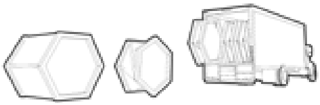


FIGURE 6.70 Folding and transportation scheme

The dimensions of the unfolded unit were 210cm (height), 190cm (length) and 242cm (diameter of the hexagon). The folded unit was approximately 70cm long (see Figs. 6.69 and 6.70). The size and folding mechanism of the shelter were governed by the transition-rotation mechanism, inspired by Jeff Beyon's origami model. [8, 9] The mechanism works like spring which extends while being rotated. The rotation angle is 120°. Therefore, the hexagons of the front and back structure stay parallel after unfolding (see Fig. 6.71). The rotation of the tube and pivot point were optimised by 3D software.

TOC

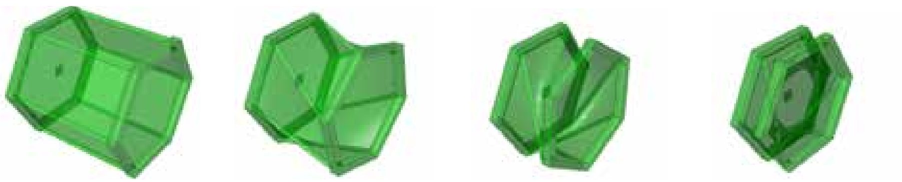
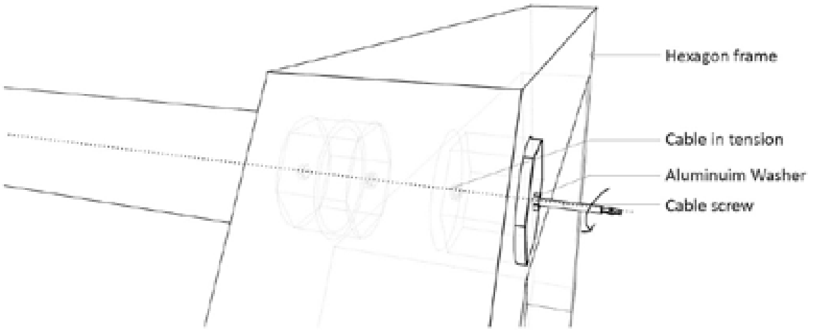


FIGURE 6.71 Spiral folding scheme borrowed from Jeff Beyon's origami model

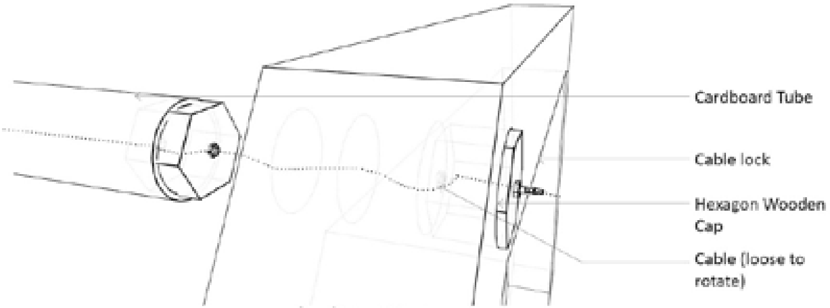
Each unit was composed of hexagonal frames made of corrugated cardboard and paper tubes with cords inside of them that held the hexagons together. The hexagonal frame was 210cm high, 242cm wide and 15.5cm thick. The frame consisted of cross-laminated 6.4mm thick five-layered corrugated cardboard. The paper tubes were 190cm long and had an outer diameter of 85cm. Their walls were 5mm thick. The tubes were able to be connected and disconnected with a hexagonal frames. Tension cables were used inside the paper tubes. Once the tubes were connected with the hexagonal frames on both sides, the tubes were fitted into the slots in the hexagons, and the cables were tensioned and locked by means of a cable tension mechanism installed at the end of the tubes. For transportation purposes, the cables were loosened and the tubes were removed from the slots (see Figs. 6.72, 6.73 and 6.74).

FIGURE 6.72 1:1 scale prototype of the HEX Shelter

FIGURE 6.73 Detail of post-tensioned cable connection between paper tubes and corrugated cardboard frame



Case1(when in open position)



Case2(when folding)

FIGURE 6.74 Detail of the connection between the paper tubes and the cardboard frame by means of post-tensioned cables

The skin of the shelter was made of PEVA (polyethylene vinyl acetate) fabric, which is biodegradable, and non-chlorinated vinyl, commonly used for shower curtains. The fabric was wrapped around the tubes and fastened with Velcro. The floor was a sandwich of honeycomb panels and OSB boards (Oriented Strand Board or flake board) on both sides of the honeycomb. During transportation the floor panel hung from the hexagonal wall panel and so was integrated with the whole structure. A door consisting of honeycomb panels provided entry to the shelter. There were two rectangular door panels in the middle and two triangular panels on the sides.

Evaluation

The idea of folding down the structure by means of a spiral movement worked fine. The folding motion required that the cords in the form of tubes from the hexagonal frames be disconnected, which somewhat complicated things. During this process the outer skin had to be detached. The skin and its connection to the structural frame should be developed further so as to reduce the risk of leakage. Another option would be to make the envelope out of some rigid detachable or foldable plates, like honeycomb panels. This would allow the shelter to be used in different climatic conditions and provide additional thermal insulation. If the envelope were made out of rigid detachable or foldable plates, they should be demountable and shipped together with the floor panel in one package. Otherwise, this shelter will be a cell that is half cardboard, half tent.

The hexagonal frame, composed of corrugated cardboard, was lightweight and strong enough to carry the floor panel loaded by 5 people and to bring stability to the whole structure. However, it was debatable if this particular use of cardboard exploited its best properties. A wooden frame would work better for this type of structure, which was proved by the Octagon Shelter, designed and built by Anna Wikiera, Katarzyna Dominiak, Aleksandra Nowotniak, Justyna Romanowska and Dorota Reclawowicz during the 2016 Summer School of Architecture (Living Unit). In this project, the same principle was used, but with an octagon instead of a hexagon (see Figs. 6.75 and 6.76). [10]

FIGURE 6.75 Octagon shelter designed and produced during the 2016 Summer School of Architecture (Living Unit)

FIGURE 6.76 Octagon shelter folded down

In actual fact, cardboard was not good enough for this project. However, it was a good way to test the behaviour of laminated corrugated cardboard under compression caused by post-stressed tubes, with positive result.

TOC

§ 6.2.9 Wing Shelter

Type of structure: Shell structure – hyperbolic paraboloid
Realisation: January 2015
Location: TU Delft
Authors: Eleftherios Siamopoulos, Ioanna Stavrou, Sander van Baalen
Design supervision: Jerzy Latka,
Prototyping supervision: Marcel Bilow, Jerzy Latka

The Wing Shelter project was a lightweight structure in the form of a hyperbolic paraboloid, composed of paper-based elements. The structure was foldable, which facilitated storage and transport. The final concept was composed of several wings, each of which consisted of four paper tubes with an attached membrane made out of woven strips of paper (see Figs. 6.77 and 6.78). Since the students did not have much knowledge of how paper behaves in such a combination, some research on weaving methods and paper properties had to be conducted. The structure itself could not be said to be a proper shelter for victims of disasters or homeless people, but it could serve as a gathering place or public space for different types of activities, i.e. semi-open school, market, religious place, etc.

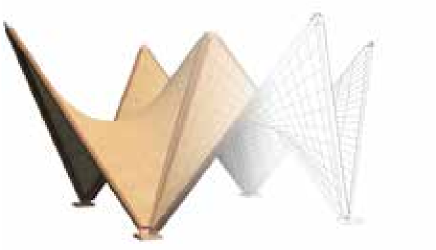


FIGURE 6.77 Perspective rendering of the whole Wing Shelter

FIGURE 6.78 Built prototype, consisting of two wings

Beams made of paper tubes were kept in position by a membrane composed of woven strips of paper. The entire unit consisted of four wings with an internal height of 3 metres at the heart of the shelter and an area of 21.16m^2. Each wing was composed of four 3.6-meter paper tubes covered with woven strips of paper. The units could be clustered together in order to cover more space (see Figs. 6.79 and 6.80).

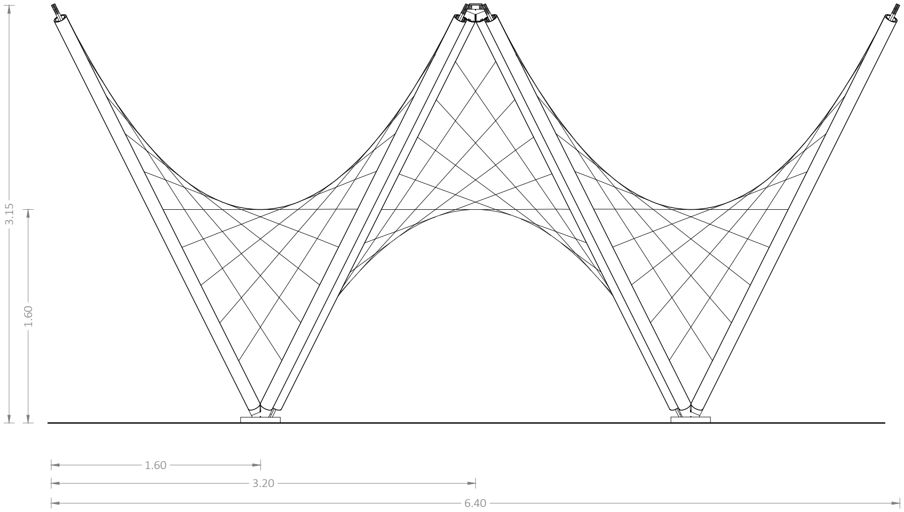


FIGURE 6.79 Side view dimensions of the Wing Shelter

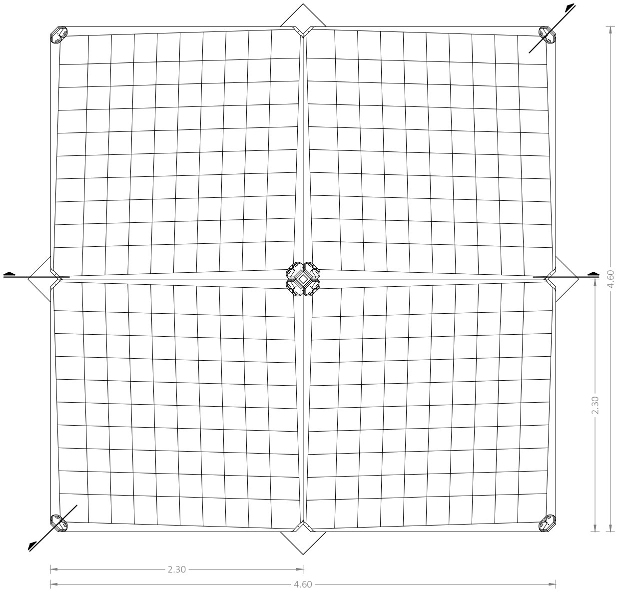


FIGURE 6.80 Plan view dimensions of the Wing Shelter

Because the paper membrane had a double curve, it was impossible to make it out of one sheet of paper. Therefore, a paper-woven membrane had to be researched. Three different weaving patterns were considered, featuring strips of paper of differing widths: a plain paper 1/1 pattern, a twill 3/3 pattern and a satin 5/1 pattern (see Figs. 6.81 – 6.83).


FIGURE 6.81 Weaving plain pattern

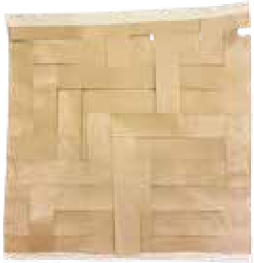


FIGURE 6.82 Weaving twill pattern


FIGURE 6.83 Weaving satin pattern

Next, tests on the tensile strength of the chosen paper were conducted. Two types of paper were tested: Kraft Liner Paper 60g/m² and Natron Kraft Paper 70g/m².

The first tests were conducted on a simple 20x20cm strip of paper, while the next few tests took into account the weaving pattern.

Tests were conducted involving the three aforementioned patterns and strips of differing widths. Each specimen was 20x20cm. Tensile tests were conducted using a universal testing machine (UTM) (see Fig. 6.84 – 6.86).


FIGURE 6.84 Tensile strength tests: plain paper


FIGURE 6.85 Tensile strength tests: plain pattern


FIGURE 6.86 Tensile strength tests: satin pattern

TENSILE STRENGTH [N] – PAPER TYPES

Paper Type	Fibre orientation	Specimens			Average
		1	2	3	
Kraft Liner Paper 60g/m^2	Parallel	820.6	455.6	444.9	573.7
	Perpendicular	336.4	576.4	388.0	433.6
Natron Kraft Paper 60g/m^2	Parallel	1224	724.0	1154.6	1034.2
	Perpendicular	-	-	-	-

TABLE 6.1 Tensile strength tests results for Kraft Liner and Natron Kraft paper

TENSILE STRENGTH [N] – WAVING PATTERNS

Waving patterns (20x20cm)	Specimens				Average
	1	2	3	4	
Plain 1x1 (2cm width)	409.1	450.9	489.2	383.4	433.2
Plain 1x1 (4cm with)	270.6	773.7	489.2	-	511.1
Twill 3x3 (2cm width)	726.395	-	596.0	663.6	662.0
Satin 3x1 (2cm width)	314.4	739.8	-	462.7	505.7

TABLE 6.2 Tensile strength tests results of different waving patterns

The structure of the Wing Shelter mainly consisted of three elements: paper tubes, paper-woven membrane and wooden connections between the paper tubes. There were two types of connections: the bottom ones, which were connected to the foundation base or were anchored to the ground, and the top ones, which held the tubes together in the air (see Figs. 6.77 and 6.78). The structure used 360cm long paper tubes with an inner diameter of 77mm and walls that were 11mm thick. The paper-woven membrane was attached to these structural elements.

In order to apply the desired tension independently to each of the strips of paper that formed a woven membrane, additional paper tubes were slid onto the main tubes in ten pieces of 36cm each. The strips of woven paper were attached to the outer paper tubes by means of dual-sided duct tape. This allowed the students to adjust the tension separately for each strip of paper. Afterwards, the outer and inner paper tubes were connected by means of nails. The membrane was woven out of ten strips of paper on each side of the structure.

'The connections between the tubes were made of laminated plywood elements. The connections were hinged, which meant it was possible to fold the entire structure in a package of 4x1 metre (see Fig. 6.87).

TOC

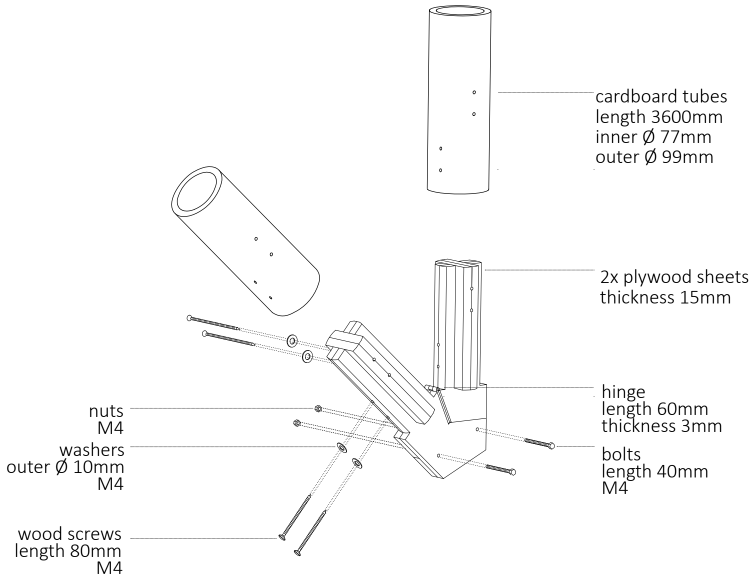


FIGURE 6.87 Detailed axonometric view of the connection in open position

Although the entire unit consists of four wings, only two were produced as a prototype due to time constraints (see Fig. 6.78).

Evaluation

The Wing Shelter project showed a new approach to using paper in architecture. For the first time, paper elements were used under tension instead of under compression. This was a better way to use the properties of paper. Paper is stronger under tension than under compression. However, creating connections with tensile elements is a big problem as paper is prone to point loads. Tensile paper elements can be connected either by clamping or gluing them to bigger surfaces. Dual-sided adhesive tape works for the second option.

FIGURE 6.88 Visualisation of a group arrangement of HEX Shelters

The hinged connectors allowed quick assembly and disassembly of the structure as well as a transformation of a big shelter into a relatively small package. Even if the project did not completely satisfy the design requirements, in that it did not create an enclosed space that clearly looked like a shelter, this approach deserves to be further worked out so as to arrive at some form of covered, semi-open spaces for public use in refugee camps (for example, for religious purposes). Triangular walls closing off the structure should be the next step of further development. Such walls could consist of honeycomb panels or corrugated cardboard plates in the form of foldable triangles attached to the paper tubes or self-standing and connected with the curve created by the woven paper. The woven strips of paper showed some inadequacy and might allow water to pass through the holes in the pattern, even if the paper were impregnated.

§ 6.2.10 The Profile: Select Your Needs

Type of structure: Columns-and-beams rod structure
Realisation: January 2015
Location: TU Delft
Authors: Eline Blom, Louisa de Ronde, Rafael Silveira, Benjamin Baron
Design supervision: Jerzy Latka,
Prototyping supervision: Marcel Bilow, Jerzy Latka

This project was all about issues associated with prefabrication, transportation, assembly, weight, adaptability and reusability.

The shelter designed by the students provided answers to all these issues. It was composed of structural components (portals), which by alternation created a different interior scheme depending on the needs of future users. Two portals were combined to form one section with a width of 1.20m (see Figs. 6.89 and 6.90).

FIGURE 6.89 Model of a single section without cladding

FIGURE 6.90 Model of a single section claded with envelope components

The sections could be attached to each other in different configurations, depending on the needs of the users. Each section was composed of four different main components: structural profiles, envelope components (roof and façade), floor components and short façade components.

Each structural portal consisted of three elements: two columns and one beam (see Fig. 6.92). The columns had different thicknesses in relation to the bending moments. The beams and the columns were composed of ten laminated layers of 6.4mm corrugated cardboard plates, reinforced with 10mm plywood at the connection points. The plywood prevented the bolts from tearing the cardboard through point loads.

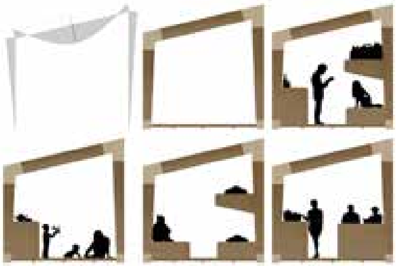


FIGURE 6.91 Different functional arrangements

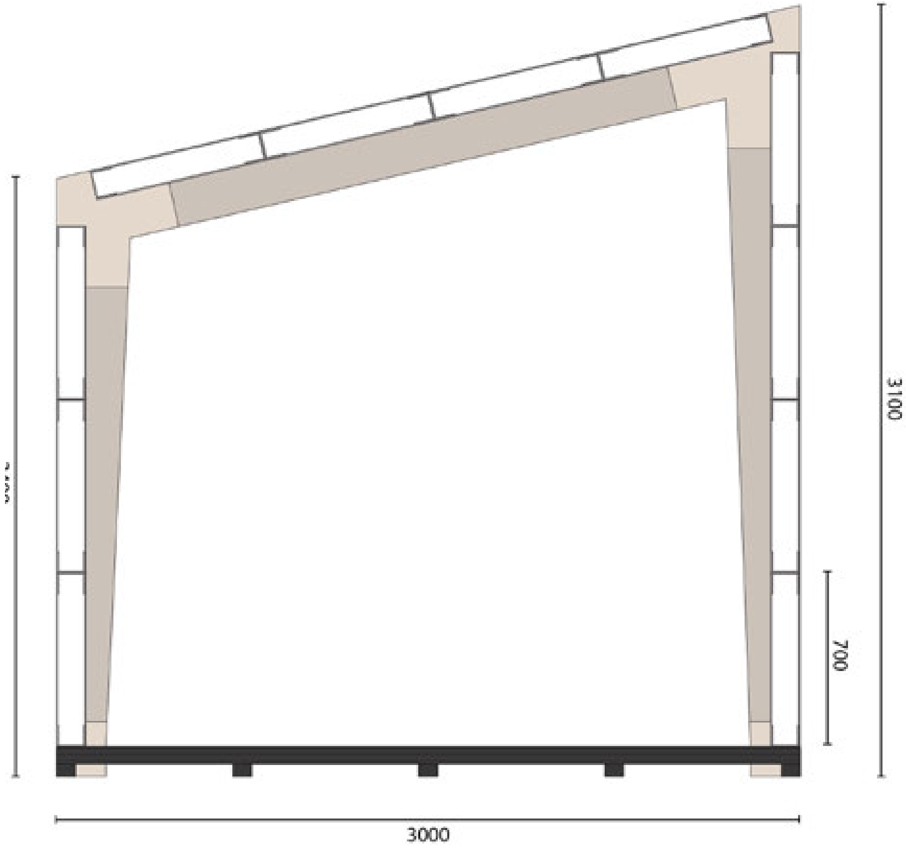


FIGURE 6.92 Structural profile

In addition to their structural role, the portals allowed the shelter to be adaptable. Different pieces of furniture were incorporated into the vertical elements (columns). These elements provided the structure with increased stability, especially in relation to lateral forces. The structural profiles were connected by the façade and roof components and allowed the shelter to be organised length-wise. Due to the fact that the different profiles could be used in different ways, it was possible to combine different functional areas, such as the sleeping zone, kitchen or living area. The shelters could also be used for other purposes: storage, study, workshop, shop, a small patient room or a meeting place (see Fig. 6.91).

The envelope components (i.e., the façade and roof components) were composed of U-profile frames held together by triangular connectors made of wood (see Figs. 6.93

TOC

and 6.94). The envelope components were produced in standard sizes and differed in terms of composition. There were typical envelope components covered from the outside with a waterproof layer of Tetra Pak material. The Tetra Pak packaging system was invented by Sweden's largest food packaging company. Tetra Pak beverage boxes are composed of six layers. From the inside to the outside, there are two layers of polyethylene, one layer of aluminium, one layer of polyethylene, one layer of paperboard and an outer layer of polyethylene (see Fig. 6.95). [11] The envelope components could be black, or alternatively they could be given a metallic finish that would reflect the sunlight and reduce the heat inside the shelter, which would be useful in warmer climates. If the structure were to be used in a colder climate, the envelope components could be filled with thermal insulation material in between the U-profiles, with a thickness of up to 10 centimetres. There were special profiles with double-glazed acrylic windows.

FIGURE 6.93 Façade component frame

FIGURE 6.94 Connections of the façade component frame

FIGURE 6.95 Cladding with Tetra Pak material

The corner elements that connected the façade elements with the roof elements were composed of honeycomb panels covered with a water-resistant finish, and L-profiles placed on their edges.

The floor components consisted of cardboard covered on both sides with 9mm OSB (Oriented Strand Board or flake board). This sandwich solution allowed the floor to distribute loads evenly on the surface. There were two different types of floor panels, one for warmer climates, and another for colder climates. The warm-climate solution was a panel composed of OSB and three layers of 2cm honeycomb panels. The version with the higher insulation value was composed of OSB panels and cardboard U-profiles with a dimension of 120x80x5mm. This created an underfloor grid which was filled up with insulation material or local soil in order to enhance thermal performance. Both types of floor panels were supported by five beams at the bottom (see Figs. 6.96, 6.97).

TOC

FIGURE 6.96 Floor sandwich composed of OSB and honeycomb panel

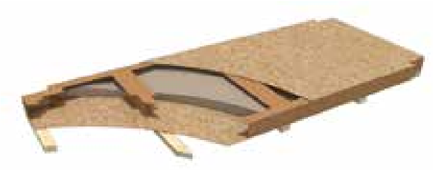


FIGURE 6.97 Floor sandwich composed of OSB and U-profile composite with cavity for thermal insulation

The short façade was the final element fixed into the structure. The short façade component was divided into three unique elements. Each of these three elements was divided into three parts which were composed and connected together in the same manner as the longitudinal façade elements. U-profiles were used as a frame, covered with a honeycomb panel and a Tetra Pak layer on top of it.

All the components were prefabricated as lightweight hybrid cardboard and wooden elements. Certain profiles could be chosen and sent to the site, where by means of basic connections with bolds they would be combined into whole shelters.

The structure was assembled section by section. Each of the sections was composed of two structural profiles, eleven façade panels, two corner elements and one floor element. Once they had arrived, the sections could be built on a levelled surface. First the floor element was laid on the ground. Then three section elements (two walls and a roof, each composed of beams or columns and envelope components) were put together in a horizontal position on the site. Afterwards, they were placed in a vertical position and fitted to the floor element. Once this sequence had been completed, another floor element could be put on the ground and the assembly sequence could start from scratch again, until the shelter had the configuration desired by the end user (see Fig. 6.98).

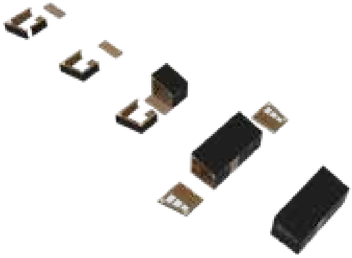


FIGURE 6.98 Assembly sequence

FIGURE 6.99 1:10 model of five sections

The sections could be clustered and connected in different ways. The structure could be lengthened by connecting the sections with the short façade. Several sections which composed one unit could be clustered in groups. Both ways of clustering, by mirroring the sections or by arranging them in a spiral shape, reinforced the structural stability of the units.

FIGURE 6.100 One section realised as 1:1 prototype with authors

FIGURE 6.101 One section realised as 1:1 prototype

FIGURE 6.102 Detail of the connection between two profiles: Tetra Pak envelope covering

FIGURE 6.103 Details of connections between wall and floor elements

FIGURE 6.104 Details of connections between roof and wall elements

Evaluation

The *Select Your Needs* profile is a solution that can be used for both emergency houses for victims of natural and man-made disasters and shelters for the homeless in the cities. The structural composition of repetitive elements that allow one to organise one's interior space is simple and clear and allows users to engage in different types of activities. The project can be adapted to different climatic conditions. Different components with different levels of thermal insulation can be fitted to the same structural system, which means that mass production for different purposes is rendered easier. Clustering the units allows one to customise one's interior, but also allows for different layouts on an urban scale. The simplicity of the construction allows unskilled labourers to erect the profile without using special tools. The risky part is using corrugated cardboard as a structural element 300cm long. When the structure was produced, pillars consisting of corrugated cardboard deflected during the process of lamination and drying. The pillars had to be clamped to the flat surface in order to avoid deflection during the lamination process. The main idea could be further developed by the use of different materials for the structural parts. Instead of corrugated cardboard, paper tubes or L-profiles could be employed. Further research should be carried out on creep of the material and the influence of the climate and the weather. Lightweight, prefabricated elements that can be combined into different arrangements should be further researched. Another part worth of further development was the envelope layer made of Tetra Pak carton board.

§ 6.2.11 Box shelter

Type of structure: Plate wall structure
Realisation: January 2015
Location: TU Delft
Authors: Juliette Goldbach, Wilem Koenen, Teun Kruip
Design supervision: Jerzy Latka,
Prototyping supervision: Marcel Bilow, Jerzy Latka

The Box Shelter was a shelter for victims of natural and man-made disasters or for refugees who have fled war zones. The shelter could be shipped to the site in a package, where all its elements would be assembled. The structure was lightweight and easily transported in the form of a package whose dimensions were 2.4 by 4.7 metres. Four of those packages fitted into a 20-foot shipping container.

The shelter could be unfolded by its future users or by unskilled labourers in several steps. In other words, the erection process and mechanism were user-friendly and easy to operate by non-professionals, just like Ikea furniture (see Fig. 6.105).

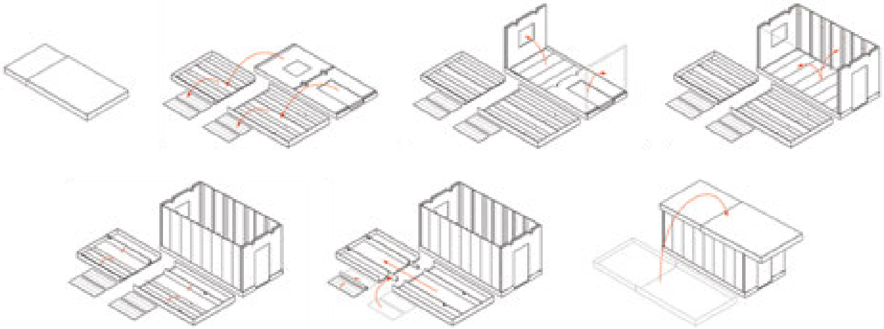


FIGURE 6.105 Construction sequence of the Box Shelter

The Box shelter could be combined with other units to form a row of shelters. Two rows in front of each other created a covered common space under the units' lean-tos (see Fig. 6.106).

FIGURE 6.106 Box shelter - visualisation

The lid of the package consisted of two parts which together made up the roof. When the lid was taken off, the remaining structure consisted of a floor and walls. The front and back walls were folded out (see Fig. 6.105). They were composed of double cross-laminated corrugated panels with U-profiles in between (see Fig. 6.110). The cavity inside the wall could be filled with thermal insulation material (lightweight foam) prior to the erection of the structure, or with local, heavier material after the unfolding of the walls. These walls were the load-bearing parts of the structure. They were connected with the floor panel through hinges placed beneath the U-shaped columns (see Figs.

6.107 – 6.109).


FIGURE 6.107 Box shelter strutre folded down


FIGURE 6.108 Box shelter structure with front wall opened


FIGURE 6.109 Box shelter structure with front and side walls opened

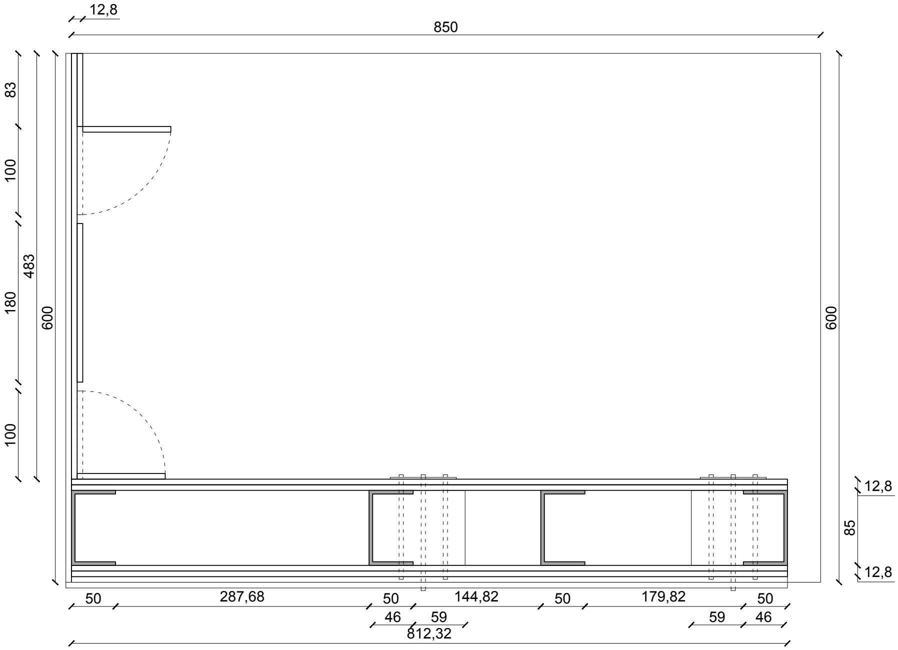


FIGURE 6.110 Detail of the load-bearing wall structure

TOC

FIGURE 6.111 Axonometric view of the structural elements of the Box Shelter

After being unfolded, the front and back walls were held in place with tension rods and nuts. The height of the two walls differed so as to create the needed slope of the roof. The front wall was 2.40m high, while the rear one was 2.20m. The door and window were placed in these structural walls.

The side walls were thinner and composed of two layers of corrugated cardboard. In the folded-down configuration, these walls were folded under the front and back ones (see Fig. 6.110). Once the Box Shelter had been erected, the side walls did not bear any of the forces. In order to make the side walls more rigid, extra flap ribs were attached. These ribs were composed of corrugated cardboard, and after the positioning of the front, back and side walls, they were opened and clamped to the floor panel. The flap ribs also functioned as the connectors between the side walls and the front and back walls.

After the unfolding of the walls, two beams made of corrugated cardboard were folded into triangles (see Fig. 6.112). These beams served as tension rods and were connected to the roof components. The two parts of the roof – the front section (bigger) and the rear section (smaller) – were connected with two inner triangular parts of the beams. This is how the roof parts were fixed together. There were two notches in the roof beams that fitted into the notches in the front and back walls (see Fig. 6.113). Once the roof was put together, it was ready to be placed over the walls. The roof beams attached to the load-bearing walls were folded from 6.4mm five-layered corrugated cardboard.

The floor component was made up of honeycomb panels covered with plywood on either side in order to prevent damage by point loading.

FIGURE 6.112 Inner beam of the roof structure

FIGURE 6.113 Connection between the roof beam and the load-bearing wall

Bending tests were conducted in order to check if the triangular roof beams would hold the roof structure. Using a Zwick Z100 testing machine, the students tested the maximal moment by means of a four-point bending (see Fig. 6.114. During the bending tests, two metal clips were attached to the top of the beam in order to divide pressure evenly across the cardboard. Three specimens with the flat side at the bottom and three specimens with the flat side at the top were tested.

The specimens were subjected to bending with a speed of 2cm per minute and with two load points caused by one pressure head. The specimens were 1000mm long and the load points were 280mm apart from each other and 360mm from the edge of the beams. At a deflection of 100mm the machine would stop automatically due to the damage caused to the material.

The beams with the flat side at the bottom only wrinkled at the top and did not tear at the bottom (see Fig. 6.115). This was because the tensile area at the bottom was bigger than the compression area at the top. The beams with the flat side at the top tore apart at the bottom around a deflection of 40mm (see Fig. 6.116).

FIGURE 6.114 Bending tests on the Zwick Z100 machine

FIGURE 6.115 Behaviour of the beam with the flat part at the bottom – visible wrinkles

FIGURE 6.116 Behaviour of the beam with the flat part at the top – a tear in the material

The beams with the flat side at the bottom had a centre of gravity closer to the tensile area than the beams with the flat side at the top (which ended up being used in the project). Therefore, the maximal moment in relation to the centre of gravity was smaller in the beams with the flat side at the bottom.

The graph of the tests showed that there was initially a small decrease of the forces after a deflection of approximately 15mm. This phenomenon, which meant that the cardboard was settled after the first load, kept recurring during the process. It was also noticeable that when the loads were first applied, the stress-strain relation was almost linear. The stiffness values of the cardboard beam could be obtained from this linear part of the graph. The maximal moment of the beam equalled 184.2 kNmm for the beams with the flat side at the bottom and 168.4 kNmm for the beams with the flat side at the top (see Fig. 6.117).

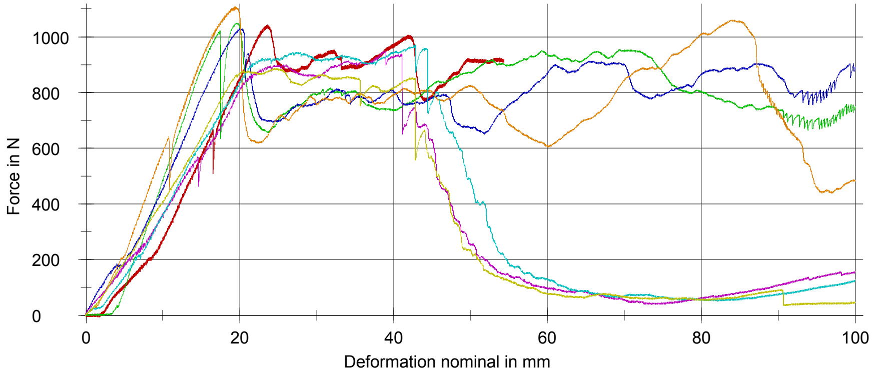


FIGURE 6.117 The graph of the bending moment tests

A prototype of the entire structure was prepared with a scale of 1:4. A prototype of the wall-and-floor connection was made in 1:1, as was the roof beam folded from corrugated cardboard.

Evaluation

The Box Shelter was a plate-wall structure. The load-bearing walls consisted of U-shaped columns covered with two corrugated boards cross-laminated to each other, so they were a lightweight and strong component – sufficiently lightweight and strong for transportation. The most promising solution the students came up with was the wall cavity, which could be filled with insulating material provided on the site. The floor panel was connected to the walls with hinges, so the whole shelter could be erected quickly. The roof was the weak part of the project. Since the roof beams were tested and found to be strong enough to carry the roof, if a problem occurred, it would probably be related to the placement of the roof on the load-bearing walls. Because no 1:1 scale prototype was prepared, it is hard to judge how difficult it would have been to install the roof on the walls. The strongest aspect of the project was its frame structure (see Fig. 6.111), clad with another material. This building components resulted in a structure that was lightweight and easy to erect. Although the front and rear walls were strong and could be properly insulated, the side walls (consisting only of a thin layer of corrugated cardboard) would not be sufficient in colder climates. However, if thicker side walls were used, the folding mechanism would no longer work properly. The hinges might also prove problematic. As they were installed in several places, point loads would occur during the erection process, with all the associated risks of material damage. Perhaps a different solution, like sliding the walls into the floor panel from above or reinforcement of the connection between the cardboard and hinges, could solve these problems.

§ 6.2.12 Papyrus Hospital System

Type of structure: Columns-and-beams rod structure
Realisation: January 2015
Location: TU Delft
Authors: Sarah Heemskerk, James Moya Jessop, Jan Kazimierz Godzimirski
Design supervision: Jerzy Latka,
Prototyping supervision: Marcel Bilow, Jerzy Latka

The Papyrus Hospital project involved a hospital system designed for people affected by the Ebola virus in Africa. The hospital, which was made of cardboard elements, could be burnt after being used in order to prevent the spread of the epidemic. The hospital was intended to be used in villages in central Africa and in rural and urban areas in western Africa. These regions are characterised by a warm and rather dry climate (monthly mean temperature is above 18°C). The rules for the treatment of Ebola state that there should be separate rooms for patients in different stages of the disease.

The main element of the hospital was the core, which contained treatment rooms that were expandable structures (see Figs. 6.118 and Fig. 6.119). These parts were expanded after the initial erection of the hospital. The core was composed of rigid and stable elements. The expandable part was composed of frames connected to each other with fabric. The core was used as a corridor between different rooms in the hospital and for storage of medical supplies. The expandable parts were designed to serve as rooms with beds in them, which could also be expanded from a small package.

TOC

The beds inserted between the frames stabilised them at the bottom (see Fig. 120).

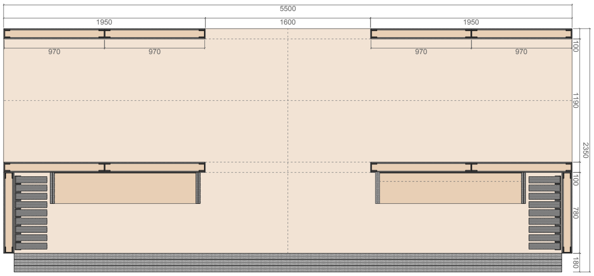


FIGURE 6.118 Plan view of the core element with folded frames

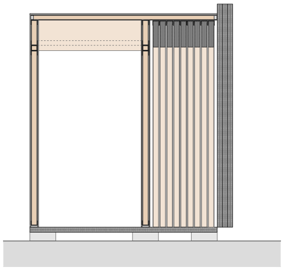


FIGURE 6.119 Section of the core element with folded frames

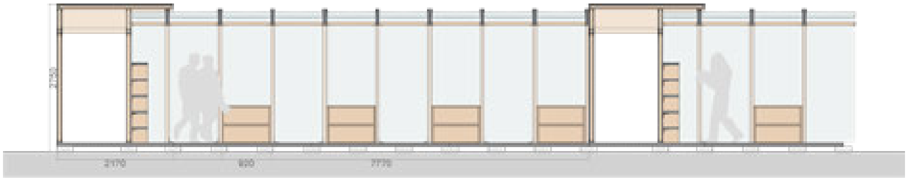


FIGURE 6.120 Section of the core element with unfolded frames

The size of the core was 550x235cm, while its height was 272cm at the highest point. In other words, the core element could be transported to the place where it was needed in a 20-foot shipping container (see Fig. 121).

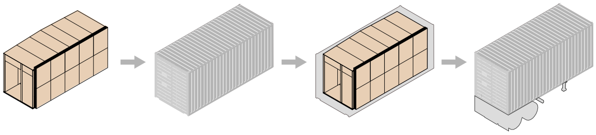


FIGURE 6.121 Transportation scheme of the folded core

FIGURE 6.122 Visualisation of the interior of the Papyrus Hospital System

The core was composed of frames clad with plates. The frames were made out of cardboard U-profiles. The U-profiles were held together by wooden blocks that were inserted between the flanges of the profiles (see Figs. 6.123, 6.125 and 6.126). The top parts of the frames were used to ensure the roof had the right height and slope. The

TOC

whole structure of the core was clad with corrugated cardboard panels that overlap the frames. This improved the connection between adjacent structural elements. Each core included folded-but-expandable parts of the treatment rooms, i.e. folded beds and shelves.

FIGURE 6.123 1:2 scale prototype; core and expandable parts structure

FIGURE 6.124 1:2 scale prototype; interior

FIGURE 6.125 frame structure made of cardboard U-profiles elements

FIGURE 6.126 frame structures made of cardboard U-profiles

The expandable parts consisted of transverse frames made out of cardboard U-profiles with fabric in between. Cross beams and foldable beds with a width of 90cm were attached to the frames in order to improve the stability of the structure when the parts were expanded (see Figs. 6.123 and 6.124). The expandable part allowed the hospital system increase its area from 12.9m^2 to 52m^2, which means that its area quadrupled.

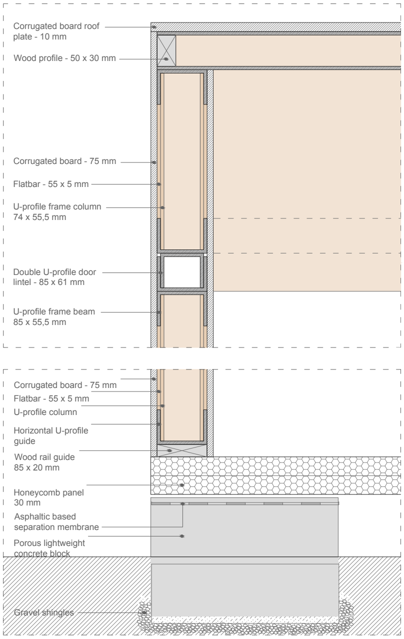


FIGURE 6.127 Detail of the longitudinal section of the external wall of the core of the Papyrus Hospital system

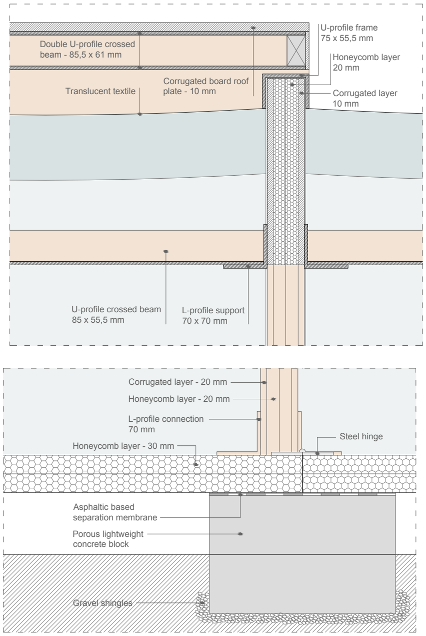


FIGURE 6.128 Detail of the longitudinal section of the expandable part of the Papyrus Hospital system

The proposed foundation was made of a porous block material. However, various solutions could be used, as long as the cardboard frame structure was raised above the ground (see Figs. 127 and 128). The prototype of the Papyrus Hospital System was built with a scale of 1:2. Although smaller structural elements were used, the structural composition remained the same.

Evaluation

The Papyrus Hospital System, which is a columns-and-beams rod structure, has good potential for further development as it provides a sustainable and suitable solution for a single-use hospital system. The elements combined into the frames are characterised by great stability and rigidness. The system of expandable frames needed to be developed with regard to stability, but the composition provided new insights into cardboard structures. Paper tubes filled with a local material or concrete could be used for the foundation. The proposed floor elements, which composed of honeycomb panels, seem to be too fragile for the area’s climatic and natural conditions, so they should be replaced with wooden plates or otherwise reinforced. The general idea behind the system could be adapted to different types of emergency buildings. A U-shape frame covered with different material and filled with thermal insulation

TOC

material could serve as a housing unit for victims of natural and man-made disasters. However, the expandable part would not be sufficiently insulated if this were the case. It could be used as a space for daily activities in the form of an expandable veranda attached to the house, while the insulated core could be used as a bedroom.

§ 6.2.13 Unbuilt projects

The projects described in the preceding sections were all realised as complete or partial prototypes with a scale of 1:1, 1:2 or 1:4. However, the students came up with other detailed designs for domes and shelters made of paper or cardboard. No full prototypes were made of these designs due to the costs involved, the lack of potential for further development, the lack of suitability of the shelter or the amount of work needed to complete the prototype. These unbuilt projects are presented in brief below.

Samuel de Vries worked on a cardboard tensegrity dome. A tensegrity (the word is derived from ‘tensional’ and ‘integrity’) is a structure whose compression elements are held up by a web of tension elements or cables. The tensegrity dome originated from the vertices of an icosahedral geodesic dome whose frequency is multiplied by three. The chosen frequency was v6, and a Z-like tensegrity pattern was adjusted to the dome. The dome was designed to be 2.8 metres high and have a 3.5m diameter (see Fig. 6.129). Paper tubes were supposed to be used as compressed elements in this design. A detail of the connection had to be designed in such a way that the tensile cables coming from different directions all met at the axis of the tube. De Vries worked on a connection involving wooden plugs and steel studs (see Fig. 6.130). The material tests and calculations performed on the paper tubes showed that the chosen type of tubes was not strong enough for such a structure and that it failed because the paper layers buckled and delaminated (see Fig. 6.130. However, if stronger tubes were used (made from virgin fibres), and if better glue were applied, it would be worth conducting further tests and verifying the potential of using paper tubes in tensegrity structures.

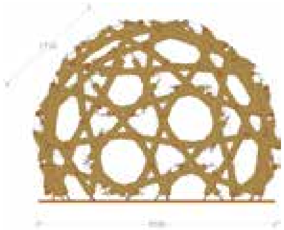


FIGURE 6.129 Drawing of the tensegrity dome

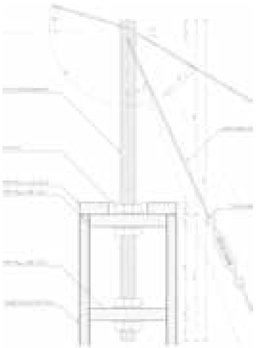


FIGURE 6.130 Detail drawing of connection

FIGURE 6.131 Paper tube compression/buckling test

The Dome of the Rings designed by Feng Liu and Melani Schafer was a double-layered structure composed of sliced paper tubes (see Fig. 6.132). The dome was 2.3 metres high and had a diameter of 4.6m. The proposed dimensions of the sliced paper tubes were 80mm (length), 300mm (diameter) and 10mm (thickness of the wall). The lower layer was connected with the upper one by inserting the paper tubes through the slots cut into the walls of the paper tubes (see Fig. 6.133). The paper tubes would intersect with each other at 40cm intervals. Then the sliced paper tubes would be connected by means of zip ties. The basic idea behind the dome was a 1v icosahedrons, which meant that the dome consisted of ten triangular flat panels which, after being bent, could be connected to each other (see Fig. 6.134). Connecting the panels would involve bending them in the positive and negative directions, so as to make the edges of the panels snap together. In order to achieve structural stability, the sliced paper tubes at the bottom would be relatively wide, while the ones at the top would gradually grow smaller. In addition, the rings at the bottom could be filled with plywood in order to make the tubes at the foot of the structure more rigid. Although the dome produced from sliced paper tubes of one single size would undoubtedly look beautiful, it was doubtful that it would function properly as an emergency shelter. Because of a lack of material, it was not possible to build a full prototype with a 1:1 scale.

FIGURE 6.132 Scale model of the Dome of the Rings

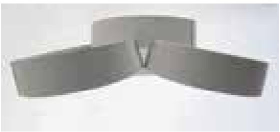


FIGURE 6.133 Intersection of sliced paper tubes

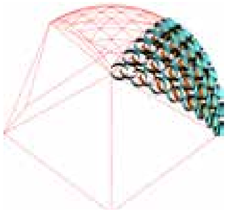


FIGURE 6.134 Single triangular panel projected on the 1v icosahedron dome

TOC

Elen Ordell and Davide Zanon designed a ‘Structure That Shades Itself’. The aim of the design was to create a shading structure which, through proper use of the properties of the material, would span the distance and looked beautiful. The materials used for the project were 7.2mm double-layered corrugated cardboard, wood and glue. A paper rope was used to create a tension ring. The students opted for a geodesic icosahedron dome with a triangular division, but the straight members were replaced with spheres which were inscribed into geodesic dome triangles (see Fig. 6.135). Each of the spheres was composed of four circles cut from the plane surface. The circles interlocked in half-in-half connections. Each circle consisted of two layers of corrugated cardboard laminated together (see Fig. 6.136). Every sphere was connected to two other ones in the plane by means of slots in the circles. The whole cloud of spheres was placed on five pillars (see Fig. 6.137). One pillar was made out of four cardboard elements combined with nine other elements in the orthogonal direction. The pillars were installed on the base ring, made out of 20cm wide cardboard circles with a diameter of 4.2m. The Structure That Shades Itself was a delicate composition whose primary function was providing shade and looking beautiful. It could be produced from more resistant material and used outside, or alternatively, it could be connected with a lighting installation and hung from the ceiling. However, it did not work well as a dome, least of all a dome used in emergency situations.

FIGURE 6.135 Part of the prototype, realised with a scale of 1:1

FIGURE 6.136 Model and prototype of a single sphere

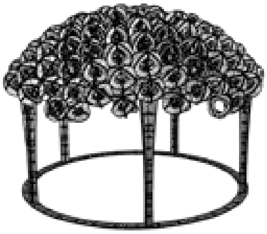


FIGURE 6.137 3D model of the whole structure

Mingjie Ning and Nick Vlaun proposed a shelter that could be folded up from a flat package by a twisting motion (see Fig. 6.138). This deployable disaster shelter was created in a shape similar to the shell of a land snail. The spiral-shaped floor plan had one entrance. The collapsible structural pattern consisted of vertical folds inwards and diagonal folds outwards. The so-called 'Shellter' had a height of 2 metres and was over 3 metres wide (see Fig. 6.139. The shelter consisted of 63 triangular panels (A, B and C) and additional top (E) and bottom (D) panels. The top E panels were connected with the A panels in order to preserve the shell shape, while the D panels were connected to the foldable floor plate. Some of the panels were detachable so that the package could be folded flat. These panels were connected with the adjacent ones by overlapping flaps that were connected by belts. A separate floor plate (which was pinned to the ground or loaded with heavy objects such as sandbags) was also connected with the shell by belts. The panels consisted of irregular triangles made out of two cross-laminated layers of 7mm corrugated cardboard. The triangles were connected by means of tape applied from both the inside and the outside. The panels were additionally covered with silicone-enhanced paper for waterproofing purposes (see Fig. 6.140). The 'Shellter' seemed to meet the requirements of the cardboard shelter. Its structural stability was proven by computer analysis, but some details needed further elaboration. The most dubious aspect of the design was the floor plate and its connection with the shell and the ground. Furthermore, the entrance to the shelter should be further developed to ensure that the conditions inside the shelter were comfortable. The structure itself could be transported in the form of flat packages, but the connections involving belts posed a risk of concentrated loads and water leakage.

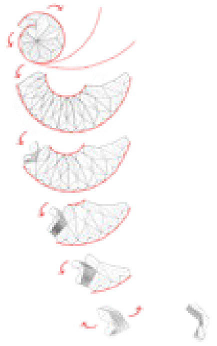


FIGURE 6.138 Folding motion of the structure

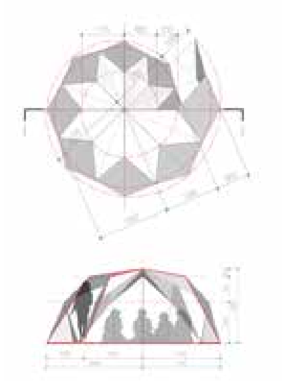


FIGURE 6.139 Plan and section of the 'Shellter'

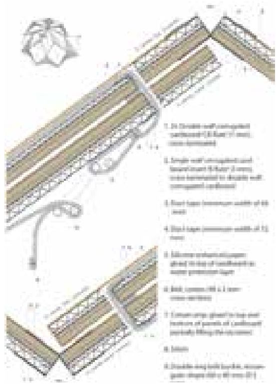


FIGURE 6.140 Detail of the connections between the panels

The dome designed by Mira Conci and Ayelt van Veen was composed of panels arranged in an alternating and cross-like design (see Fig. 6.141). The panels served as the structural elements of the dome. Each cross-like panel consisted of two flat boards with slots. Vertical and horizontal boards were inserted into each other (see Fig. 6.142). The boards were sandwich panels made of corrugated cardboard with Styrofoam in between

TOC

(see Fig. 6.143). Additionally, triangular plates were connected with the cross-like panels by means of tie wraps in order to seal the space off from the external conditions. Although the dome looked impressive, it did not satisfy the requirements, which were to use cardboard as a building material. In order for this structure to work, the panels should be made of aluminium or plastic layers with thermal insulation material in between for greater stiffness. The connection between the panels caused point loads, which are hazardous when cardboard is used as a structural material. The openings in the panels would have to be covered with some extra (translucent) material. However, water would pose the greatest threat to the structure. Rain water would flow into the valleys created by the intersecting connections, thus damaging the material.

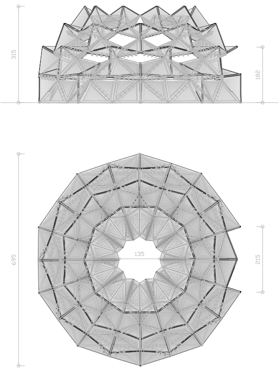


FIGURE 6.141 Side and top view of the dome

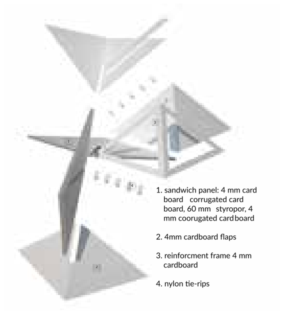


FIGURE 6.142 Exploded detail of the cross-like connection

FIGURE 6.143 Prototype of the cross-like connection

Rens Ottens and Floris van der Burght proposed an emergency modular building system of foldable components such as walls, floors and a roof, which would minimise the volume of the structure during storage and transportation. Each of the emergency units consisted of four panels that were self-supporting. The panels were connected together by hinges. After the unit was erected, the hinges were locked by means of a pin. The hinges also served as connectors between the single units. First and the last units of the row were closed off by a gable wall reinforced with diagonal bracing (see Fig. 144). Once the shelters had been erected, the wall, roof and floor panels were unfolded. Two motions were required to unfold the panels. The folded flaps were first rotated by 90 degrees, then folded back by 60 degrees. This movement allowed the inner flaps incorporated into the panels to open and lock. This is how the panels gained the required thickness and stability. The motion of the flaps of the panels was of the 'only-one-direction-possible' variety, which made the whole process quite simple. The authors called the principle behind their project 'movement from 1D to 2D to 3D'.

Although no full prototype was realised, the wall and floor panels were built and tested (see Fig. 6.145). As the creasing lines in the flaps of the panels had to be very precisely positioned and bruised, a special bruising machine had to be built first. There was no time for this, which is why no full prototype was created.

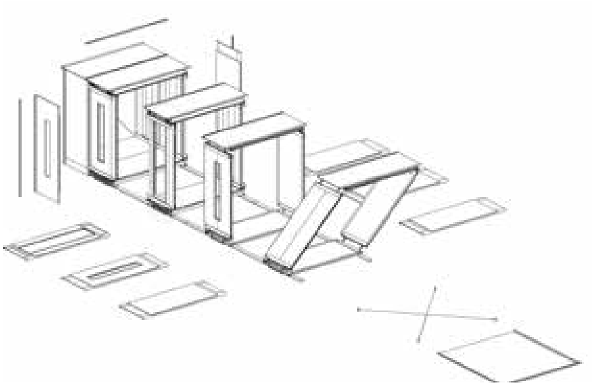


FIGURE 6.144 Building-up scenario

FIGURE 6.145 1:1 scale prototype of the floor and wall panels

The Outreach was an expandable shell shelter designed by Jik Mosch and Mitchell Mac-Lean. The design of each unit involved four shell segments of increasingly small sizes, which allowed them to be pushed into each other for storage and transportation purposes. When the Outreach was placed in the desired location, the shells were slid from each other to create a shelter with an area of approx. 14m^2 (see Fig. 6.146). Each shell segment was composed of primary and secondary structures and foundations (see Fig. 6.147). The primary structure was composed of corrugated cardboard arches, whose corrugation lines followed along the curvature of the arch. There were four arches in each of the shells. The arches were connected to each other by secondary structural elements – horizontal paperboard L-shapes. The L-shapes also served as shelves for additional thermal insulation. The arches had varying thicknesses, with the last arch of each segment overlapping with the first arch of the next segment. The overlapping arches were bolted together in order to stabilise the structure and keep the segments in position. Other structural parts of the shelter included the wooden floor and foundation. The floor and foundation of each segment consisted of two plywood boards that were hinged to the wooden box foundation. While the Outreach was inserted, the floor plates were put up in order to create enough room for the other shell segments. When the structure was opened, the floor panels were put in horizontal position and the floor legs were unfolded. The foundation boxes could be filled with material such as gravel or sand for better stability. The walls of the shell segments were covered by rolled-up paper. However , other cladding options were considered, such as pouring concrete over the exterior or cladding the shells with clay for better insulation. The first and last shell were closed off by gable walls with openings. The prototype of the structure was only partly executed. It was hard to evaluate the project on the basis of the work completed, because the most complicated parts, such as the connections between the segments or the outer layer of the structure, had not been completed (see Fig. 6.148).

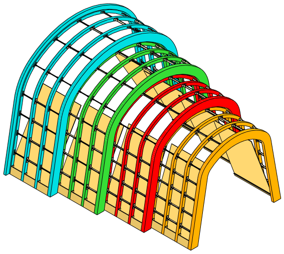


FIGURE 6.146 The structural parts of the Outreach

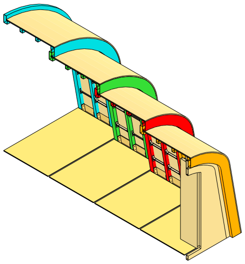


FIGURE 6.147 The Outreach section

FIGURE 6.148 Partly realised prototype

§ 6.3 Conclusions

The projects presented in this chapter, designed and executed in the form of prototypes, show different approaches to cardboard as a building material. Most of the projects realised had foldable structures. The paper-and-cardboard structures are reminiscent of origami folding patterns, and many students made good use of the flexibility of the material. However, folds also give rise to problems. Since the material used for these projects was not a thin, single sheet of origami paper, but rather thicker paper, the connections between the foldable elements required special attention. There were several types of connections between plates that ended up creating foldable structures. Duct tape and hinges (including a so-called 'live hinge') were the solutions used most often. Duct tape proved strong enough to be used in real situations, but the hinges proved to be a more risky proposition. First of all, connecting the hinge required screwing/bolting or gluing. Point connections involving bolts can easily damage paper or cardboard. As long as the elements are not too big and therefore lightweight, they can be folded without any risk of damage. Folding up big elements would result in significant bending moments at the connection with the hinges. Therefore, projects involving such hinges had to be limited in size and it would be difficult to make the folding parts bigger than just a few square metres. Another noticeable trend was structures composed of prefabricated components that were connected to each other by joints, mainly screwed or bolted to each other. Intersecting and sliding solutions were tested, as well.

If the projects were to be categorised by the structural system involved, the largest number of projects were shell-plate structures, followed by shell-strut systems. Other shell structures included hybrid solutions combining both plates and struts. In addition to systems whose structure consisted of a shell, columns-and-beams systems were used. The latter incorporated a structural system based on walls, floors and roofs made of plate.

The foldable structures had the advantage of quick erection and a relatively small volume when folded down for storage and transportation. Depending on the structural system used in these projects, the riskiest part was the stability of the structure after it had been unfolded. In some cases the material used seemed too weak to hold dead loads and loads caused by wind and snow. Some of these projects could be used as a temporary shelter which could be upgraded if necessary by pouring a concrete or resin layer on their surface. The inhabitants would not even have to leave the shelter for this. On the other hand, those projects that incorporated several individual components and were assembled at the building site proved more rigid and stable. Although their building process was more complicated and required the use of extra tools and sometimes specialist labour on site, the volume of the components in their packages was also minimised.

One aspect that had to be taken into account was that even if emergency shelters are built for several months or perhaps a few years, they may well be used for much longer than that. Therefore, it was crucial that the structures be safe and stable in the long term.

Most of the projects submitted were attempts at creating an emergency shelter, but there were several projects that did not meet the requirements of emergency architecture. Some of the projects seemed to revolve around the idea that a shelter was something that could be delivered at an emergency site quickly, while others would require a fair bit of time to be erected. Most of the proposals assumed that the structure would have inhabitants, but there were also interesting examples of structures that could serve as public spaces, retail utility units or hospitals. Ideally, a structure would be able to be adapted to different types of use.

TOC

The type of material most commonly used for the production of the prototype was corrugated cardboard. This material is produced in big quantities, therefore cheap, and can be used in construction. The downside of corrugated cardboard is its anisotropy. Corrugated panels are weak when subjected to forces perpendicular to the direction of the corrugation. Cross-lamination of the corrugated cardboard plates may mitigate this problem. However, corrugated cardboard is weak when forces are applied in the perpendicular direction to its surface. Fifteen out of the nineteen projects presented at the end of the course incorporated corrugated cardboard, mainly because it is widely available and cheap. However, when forces are applied perpendicular to the surface, honeycomb panels are a better solution than corrugated cardboard. In those projects that involved floor panels, cardboard honeycomb was the most used material. The floor panels were covered with additional material such as plywood or OSB panels to prevent point loads and to spread the forces more evenly on the surface. Both paper tubes and cardboard L- and U-shapes were used in the shell-strut and columns-and-beams systems submitted. Paperboard and paper were used in three projects. In the case of the SCOLP project, the difficulties associated with cutting and laminating the paperboard connections were too complicated for mass production, although the project showed great potential.

As mentioned before, the types of connections used between the various structural parts depended on the structural system and erection method used. The foldable structures featured elements connected by duct tape, textile or hinges. The hinges were bolted into the material. Projects involving columns and beams used joints made out of wood. Such joints were connected with the strut elements by means of glue, nails or screws. One exceptional solution was the use of cardboard as a joint member. In the SCOLP project, the paper tubes were connected by laminated connectors made of paper board and locked into each other by cardboard wedges. The Curved Fold Dome used corrugated cardboard members, but the members were connected to the struts by means of zip ties, which caused the material to tear.

Intersecting structural elements were used in the Waffle Dome and Dome of the Ring projects and in the dome designed by Conci and Van Veen. This type of connection required extra reinforcement in the form of an outer layer that would keep the elements in place, or bracing, or additional connections between the intersecting parts. Another type of connection that was used was a post-tensioned connection between cardboard hexagons and paper tubes in the HEX Shelter project.

Post-tensioning and connections involving wooden joints were the most durable and the most consistent with the properties of the material. These methods should be considered in the further development of emergency shelters.

TOC

A wide range of ideas were presented with regard to methods to connect the structures to the ground. Some projects included platforms, which were simply positioned on levelled ground. Such platforms were often designed as sandwich panels composed of wooden plates (plywood, OSB) and honeycomb panels. While honeycomb panels could work as a form of thermal insulation, they should not to be used in direct contact with the soil unless they have been thoroughly impregnated and waterproofed. However, even after impregnation, cardboard can be easily damaged by capillarity, as happened at Hualin Primary School. Therefore, designs that involve cardboard being used in direct contact with the ground should be avoided.

There were also several projects that used boxes (made of wood or cardboard) as a basic structural element. These boxes could be filled with gravel or sand. However, as mentioned above, cardboard is not suitable for such solutions.

Anchored foundations following the platforms were most commonly used in dome-like structures. Out of all the proposed solutions, the ones that should be taken into account as functional and safe in relation to the material used are those in which structural elements (timber and cardboard) were kept away from the ground. The Papyrus Hospital System and Profile: Select Your Needs are projects in which a suitable foundation in the form of concrete blocks, paper tubes filled with concrete or other solutions (like plastic containers or ground screws)might be successfully applied.

One of the key issues in the design of emergency structures is thermal insulation. As demonstrated in Chapter 5, emergency structures are needed in every kind of climate. Therefore, we must design solutions specific to a certain region or propose a universal system that can be adapted to different climates. Most of the projects submitted in the course were designed for hot climates. Several of these projects took into account temperature changes, insulation and annual rainfall. The most desirable solution would be a universal structural system which can be adapted to local circumstances by means of different types of the panels. This idea was presented in the Umbrella Shelter project and the Profile: Select Your Needs project, in which two different types of envelope were proposed. A project with a foldable mechanism, which incorporates structure and envelope elements into one system, will not meet this requirement.

Although impregnation is a crucial aspect of building with cardboard since it protects structures from moisture, water, fire, insects, etc., the prototypes presented in the course mainly focused on geometry, structural system, the type of material used and its composition, storage, transportation, production and construction issues. Impregnation was not taken into account here. On the other hand, the process of designing and prototyping was an important part of the assignment. Individual designs that were later merged into group projects were first worked out on paper by means of sketches and brief descriptions of proposed systems and solutions. Then computations were carried out, while at the same time scale models and mock-ups of parts of the structures were created. The physical models and mock-ups allowed the students to investigate details of the structure, such as its stability or the connections between the various elements, and also helped them avoid structural problems in the early stages of the designing process. In some cases material tests had to be conducted in order to gather fundamental knowledge of the material and its behaviour, which was then included in structural calculations. The final part of the process – constructing the prototypes – was the ultimate verification of the architectural solutions implemented. The prototypes showed what the actual construction process might look like, what kind of tools could be used and how many people could erect a shelter in any given amount of time. It also brought production processes of prefabricated components or shelters to life for the students. The prototypes that were built allowed the students to assess what was possible in terms of storage and transportation.

Some of the projects presented at the end of the course were very useful and had significant potential for further development. Even if they were unsuited to being used as emergency shelters, they could be treated as interesting structures that could be used for temporary events, expositions, festivals, etc.

For the sake of further research that will come up with the optimal solution for emergency structures made of cardboard, the following performance indicators drawn from realised prototypes should be taken into account, developed and implemented in future projects:

- Function-focused design – the design must be simple so that regular people without specialist knowledge can assemble the structure.
- Easy storage – the volume must be minimised to allow the structures to be stored in a warehouse in large quantities.
- Easy transport – the elements and components of the structures should fit into a lorry or shipping container. They should be folded or individually wrapped in a way that allows large numbers of shelters to be transported, without any wasted space caused by half-empty packaging.
- Lightweight elements, components or entire structures in the form of prefabricated products – the products should be able to be moved from the truck and carried at the building site by hand. This will reduce the costs of transportation and prevent special tools or machines from being needed on site.

TOC

- Simple structures – the more basic the structure, the more likely that people without much knowledge of construction and without specialist equipments will be able to erect it

- Height – the height of the shelters should not exceed five metres, so that no additional equipment will be needed to erect them.

- The structure could be composed of integrated load-bearing elements or have the form of frame structure – i.e, a load-bearing system filled with thermal insulation panels. The first option, however, reduces the likelihood that the shelters will be able to be used in different climatic conditions.

- The floor panels should be kept away from the ground, thus minimising direct contact between the cardboard elements and water, which will in turn reduce capillary action. The possibility of creating of an Under-Floor Air Distribution (UFAD) system could be explored, too.

- In order to minimise ecological damage caused by the shelters, the Light-Touch-to-the-Ground approach should be adopted. In general, this involves the use of pile foundations, ground screws or other solutions for raised floor slabs.

- The structure should be designed as a temporary structure, but it should come with a five-year warranty.

- The structure should be created in such a way that the parts of the shelter can be replaced, retrofitted, fixed, improved, rebuilt or rearranged, without the inhabitants having to move out.

- The structural system should be universal and flexible, which means that it allows manufacturers to produce smaller and bigger units from mass produced paper elements

- The shelters should be able to be clustered in bigger groups – for example, in the form of row houses, courtyard houses or a nested arrangement of units.

- The shelter should have a neutral shape that will be acceptable to inhabitants of different backgrounds. Possible customisation is advisable, for instance in the form of printed colours or elements added to the façade.

- The shelters should have a basic shape with straight vertical divisions which allows the inhabitants to use commonly available furniture.

TOC

- The material and impregnation methods used should allow down-cycling or recycling of the material after the lifespan of the shelter.
- The amount of waste produced by production, construction, usufruct and demolition should be minimised.

The above indicators will be used as aspect analysis or input data in further research by design, development and prototyping of transportable emergency cardboard houses.

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TOC