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# ALTERNATIVE USES OF PAPER AND CARDBOARD IN ARCHITECTURE AND CONSTRUCTION

BY

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**Abstract.** This paper developed an analysis of the relevant uses of paper and cardboard in construction and architecture, as a basis for information for future studies and research. In this context, based on data from the literature it is demonstrated that it is possible that cardboard products with sufficient compressive strength can withstand structural loads, thus providing an alternative to the use of traditional construction materials (concrete and steel), in the field construction and architecture. There is also the potential for the use of cardboard as a material in the construction of assemblies as construction elements, such as panels for walls, roofs and floors, as well as the development of short-lived or temporary buildings. Some houses are made of waste paper and cardboard and can be recycled for the manufacture of cardboard. These recycling processes involve less energy and clearly less raw materials than the production of many other materials.

**Keywords:** building materials; cardboard tubes; environmental impact; insulation; recycling.

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## 1. Introduction

Paper and board made from cellulosic fibers are used for printing or packaging, but also in aviation industry or for the construction of various inside house elements, including furniture and doors. Their use in construction and architecture dates back to the industrial revolution, with a wide range, if we refer at least to the embossed decorative wallpapers or floral designs covered with plaster from the western Victorian stage, to the transparent and delicate shoji from eastern Japan (Eekhout *et al.*, 2008; McNeil, 1992). Today, paper and cardboard products are used in construction, less for decorative purposes, than for honeycomb door cores, plasterboard, waterproofing bitumen membranes or laminated composite materials for furniture, kitchen surfaces and printed boards circuits for electronic and electric devices (Addis, 2006). At present, there is still potential to develop new construction methods and products using paper or paper waste, as a challenging and interesting field.

The great advantage of paper and its by-products and, first of all, of cardboard is that they are cheap, light and durable, flexible in shape and color, recyclable (Latka, 2017; Schonwalder, 2016). The discovery of opportunities for the efficient use in construction of materials of this nature, renewable and recyclable to a large extent, can be a step forward in the movement towards sustainable development. As a structural construction element, corrugated cardboard has many advantages. In addition to being a relatively low-priced material, it has significant insulating properties (thermal and acoustic), it is easily recyclable and can be made from renewable sources. The most important property of corrugated cardboard, as a construction element, is that it has a high degree of structural strength and rigidity (Russ *et al.*, 2013; Secchi *et al.*, 2016).

Despite these proven advantages, the growing popularity of corrugated cardboard as a building material has remained relatively stagnant over the years, mainly due to the perception of limitations that include vulnerability to humidity, fire and temperature, as well as its sensitivity to ultraviolet light and various chemical substances. Solutions to many of these problems are currently being addressed and tested by researchers in the field (Abdel-Mohsen *et al.*, 2014).

Therefore, data from the literature show that it is possible for cardboard products with sufficient compressive strength to withstand structural loads, thus providing an alternative to the use of traditional building materials (concrete and steel) in construction and architecture. There is also the potential for the use of cardboard as a material in the construction of assemblies as construction elements, such as wall, roof and floor panels, as well as the development of short-lived or temporary buildings. However, there are few studies that use cardboard waste for these purposes. In this context, an analysis of the relevant uses of paper and board in construction and architecture has been developed in this article.

## 2. The Potential of Paper and Cardboard as a Building and Thermal Insulation Material

Cardboard was analyzed and explored primarily for the main purpose for which it is produced: as a material for the production of packaging, but the potential and attractiveness of this material for use in architecture and construction have determined the need for studies aimed at such an alternative approach (Cripps, 2002; Lyons, 2014). In the following, leaving aside the paper (it is considered that if it exceeds 200 g/$m^2$ it is considered as cardboard), a brief presentation of the investigations performed on the use of the four main types of cardboard is made: solid cardboard, corrugated cardboard, cardboard corrugated with honeycomb structure and cardboard tubes, in architecture and construction. Such research has been conducted in Europe - mainly in the Netherlands, at the Technical University of Delft (TU Delft) and in Switzerland, at the Federal Institute of Technology in Zurich (ETH Zurich). Some of the investigations carried out in Delft are included in the book of Eekhout *et al.* (2008). The book is dedicated to the detailed presentation of the methodical research program undertaken by the Department of Construction Technology within the Dutch University to promote cardboard in this field. The book also addresses other topics, such as structural engineering and design in the field of paper and cardboard or the mechanical properties of cardboard, but likewise some applications, such as the process of designing and building a cardboard exhibition pavilion, applying cardboard for partition walls, house cardboard or cardboard dome, as an example of an engineering approach.

At the Federal Institute of Technology in Zurich, in 2009, two doctoral theses focused on the use of cardboard in construction were defended. The first of these is a conceptual approach to cardboard constructions in architecture (Ayan, 2009). The author's original contribution to this thesis addresses the perception of cardboard buildings from a social point of view. Other topics focus on environmental issues and the development of a constructive component with a low impact on the environment. Here the author makes comparisons applying the life cycle assessment method for various types of cladding materials with corrugated core panels such as: steel, aluminum, wood plywood for external use and fiberglass reinforced plastic plywood. After determining the environmental impacts of these components, the author proceeds to compare walls made of the four types of cladding designed with a cardboard core of 100 mm, with conventional walls of 200 mm built of brick or concrete. It turned out that the biggest impact on the environment has the panel covered with fiberglass-reinforced plastic and then follows in descending order, the panel with steel faces, then wood plywood, aluminum and in last places the conventional concrete walls and brick. From the analysis of prices, weight and values indicating the degree of thermal insulation performed simultaneously by the author, it resulted that the higher environmental impact of composite panels with corrugated core can be offset by lower weight and price and superior thermal insulation properties on which presents them. The author draws attention to an important element.

Thus, from the point of view of the thermal insulation coefficient λ of corrugated board, its value would depend on the orientation of the corrugation towards the ground, having values twice lower, so it is more advantageous from the point of view of thermal insulation in case of orientation perpendicular to soil (Fig. 1), compared to the orientation parallel to the soil (b). The values presented refer to the cardboard core without impregnation with adhesive, because the impregnation decreases the thermal insulation properties (Ayan, 2009) using for calculations in the case of impregnated corrugated cardboard the value λ = 0.15 W/mK. The data shown in Fig. 1 also shows the extent to which the height of the corrugation determines the thermal insulation properties: the higher the height of these corrugations, the greater the air gaps determine a better thermal insulation (corrugated board A, B or C) compared to cardboard E with the highest height small ripple.

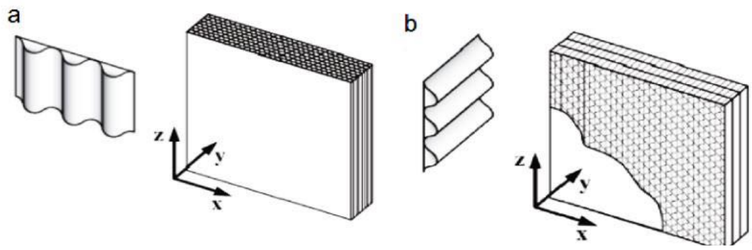


Fig. 1 – Coefficients of thermal insulation in relation to the direction of corrugation of cardboard (Ayan, 2009): *a* – Corrugations perpendicular to the ground: cardboard with low corrugation height (E) λ = 0.09 W/mK; *b* – corrugated board with high heights (A, B or C) λ = 0.045 W/ mK; Corrugations parallel to the ground: λ = 0.09 W/mK.

Based on previous investigations, 5 types of variants of composite panel walls with corrugated cardboard core usable in construction were discussed:

a) Translucent wall with fiberglass-reinforced plastic plywood with a total thickness of 30 cm and a thickness of 3 mm fiberglass-reinforced plastic layers. The cardboard is impregnated so that a thermal insulation coefficient (or heat transfer coefficient, U) value of the wall of 0.46 $W/m^2K$ is reached, which exceeds the Swiss Minenergie standard for walls of 0.2 $W/m^2K$, but falls within the standard for windows of 0.7 $W/m^2K$. It can be used as a replacement for a glass wall, being much lighter and less brittle than this.

b) Wall with a high degree of thermal insulation made of gypsum layers with a thickness of 1.5 mm as plywood. However, due to the impregnation of the corrugated cardboard, a total thickness of 72 cm of the wall is needed to meet the requirements of the Swiss standard. Using the latest generation of gypsum boards this composite wall maintains its structural strength and rigidity even when faced with moisture.

c) The same 1.5 mm thick gypsum layers used as plywood, but this time the corrugated cardboard core is not impregnated, only a 45 cm thickness of the wall is needed if the direction of the corrugation is parallel to the ground. It can be used as a partition wall or even as an external load-bearing wall.

d) Conventional sandwich wall of industrial type with a thickness of 45 cm - the cardboard is not impregnated, and the corrugation direction is perpendicular to the ground ensuring a thermal insulation coefficient of 0.05 W/mK. Fire and humidity problems are solved with 1 mm thick steel plating. The wall reaches a U = 1.2 $W/m^2K$ and can be used on structural walls, facades or partition walls.

e) Conventional industrial sandwich wall, 30 cm thick. It is also plated with 1 mm thick steel. The direction of corrugation is also in this case perpendicular to the ground, ensuring a thermal insulation coefficient of 0.05 $W/m^2K$ for the cardboard core, and the U value of the wall is 0.16 $W/m^2K$. It can be used as the previous one as an exterior wall, curtain wall or interior partition wall.

The author used for the evaluation of the life cycle of the analyzed variants. An important issue concerns the structural aspects of the cardboard architecture, which involves the testing and analysis of corrugated cardboard usable in sandwich-type composite panels for the composition of the walls. The tests are more focused on honeycomb corrugated cardboard that has the best qualities for use in construction (Ayan, 2009). These tests provide the basis for the analysis of the possibilities of applying cardboard in the field of architecture, considering the relationship of the use of this material with its defining function of space. Several types of walls were identified, each with different characteristics. The geometric pattern of the walls has been modified to control the light, the degree of sound insulation or to adjust the interior ambience and the quality of the space. The conclusions of the studies show that the biggest threat to the corrugated cardboard core with the honeycomb structure are humidity and fire. The removal of these shortcomings has been tested by impregnating the core with various inorganic substances, but the realization of the impregnation process remains incomplete in the case of thick corrugated cardboard components so it is necessary to fine-tune this process.

There is a preference for processes or materials inspired by nature, such as corrugated cardboard with honeycomb structure and this trend became even more evident after the launch in 1997 of the book of Benyus (2002). In this context, another work was done at ETH by Pohl (2009). After a presentation of paper and cardboard, how to produce them and their properties in the introductory chapters, part of the paper is dedicated to corrugated cardboard with honeycomb structure, presenting both mechanical and thermal properties and fire resistance. Next, the influence of moisture on the cardboard with the honeycomb structure is addressed and measures are proposed to reduce this influence. The results of impregnation by immersion in various waterproofing agents are analyzed experimentally and it is shown that the best results are obtained by impregnation with a commercial agent called TX Direct Wash, gypsum and cement (Portland concrete).

**Tubes** are the most common type of cardboard used in construction, although there is relatively little work on this topic. Bank and Gerhard (2016) show in their paper that cardboard tubes are mainly used globally as a support for rolling materials, whether it is paper, film, textiles, metals or others. The use of cardboard tubes for formwork concrete in circular columns is indicated as an application in construction, rather than for architectural structures designed primarily by the architect Shigeru Ban (http://www.shigerubanarchitects.com/). Shigeru Ban's architectural structures consisting of such tubes were designed using a rigorous structural engineering approach, which included special treatment of the tubes to inhibit moisture penetration, material and structural testing for structural components and junctions, structural analysis and design for ensure appropriate structural stability, safety and availability of services. In these projects Ban has collaborated with structural engineers, large international structural firms and large universities in Europe and Japan (Hill, 2014; Meynent, 2008).

Bank and Gerhard (2016) analyzed the use of cardboard tubes in construction engineering in circular column formwork. The tubes used for this purpose are often called sonotubes, because the patent for their manufacture and use was obtained by the American company Sonoco in 1954. They are currently also produced in Europe, but from the estimate required for such tubes from the subsidiary of a manufacturer (Rapidobat) in our country for the realization of a foundation on pillars in the case study, resulted in a very high price of these tubes. Cardboard tubes currently on the market are not intentionally made or optimized for use as structural elements in architecture and those who want to give them such a use must proceed with caution and agree with manufacturers to meet structural and environmental standards. But Shigeru Ban and several other architects have shown that many large structures made of such tubes have successfully withstood the external environment for more than 20 years. Those that have been built for temporary exhibitions have the advantage that they can be recycled after use (Galfetti, 1977).

A number of papers address the use of corrugated cardboard as a thermal insulator (Asdrubali *et al*., 2015a; Foss *et al*., 2003; Shi *et al*., 2013). In terms of thermal properties, as a result of experiments performed on panels made of corrugated board with high corrugation type C, small corrugation type E and one type sandwich with two sides type E and core type C, values of the thermal conductivity coefficient $\lambda$ very close to those mentioned by Ayan (2009), namely 0.0524 (compared to 0.05) W/mK (Asdrubali *et al.*, 2015a). Also, experiments have shown that the sound insulation properties of these panels are meritorious and they can be used for thermal insulation in buildings, especially in interior partitions (Asdrubali *et al.*, 2015a, 2016; Baldinelli *et al.*, 2014). Therefore, their area of use can be extended to acoustic control of open outdoor space or in case of temporary exposures. A particularly important aspect refers to the use of recycled old corrugated board (waste without paper potential, used corrugated containers (Old Corrugated Containers - OCC)) as thermal insulation in buildings, in connection with which they were found few publications. Russ *et al.* (2013), concerned about the problem of corrugated paper waste faced by their country, Slovakia, examines the possibility of using structural panels of this origin in the manufacture of furniture or construction, in the production of thermal insulation panels or construction panels for partitions. Various types of panels were made, some of which were made of old corrugated cardboard (Fig. 2) on which tests were performed on thermal conductivity and flexural strength.


Fig. 2 – Old corrugated panels analyzed for potential use in construction (Russ *et al*., 2013).

The adhesives selected in the experiments for gluing the corrugated cardboard layers that form such a sandwich panel were Duvilax BD-20 and UHU. The experiments showed that, in terms of thermal insulation properties, the best results are obtained when using a quantity of 100 g/m$^2$ of Duvilax BD-20, for a two-layer corrugated board, with the value $\lambda$ = 0.045 W/mK, and in terms of flexural strength resulted a value of 1.42 MPa, both sufficient both for proper thermal insulation and for the handling and strength of these panels over time (Russ *et al*., 2013).

## 3. Applications of Paper and Cardboard in Construction and Architecture

Research on increasing recycling and developing environmentally friendly, with good performance, low-cost materials as alternatives to many currently used in various fields of application, particularly in construction and architecture, is relatively intense, especially to minimize the use of unsustainable or harmful materials (mineral wool, materials from fossil sources, expanded polystyrene) and incorporates a large amount of energy (Asdrubali *et al.*, 2015a, b; Pargana *et al.*, 2014). The European Directive 2010/31/EC calls for the construction of near-zero energy buildings by 2020, thus recognizing that green building strategies can be extremely effective in terms of fossil fuel savings and greenhouse gas reduction (EC Directive 31, 2010). Thermal insulation is recognized as one of the most efficient ways to ensure energy savings (Battista et al., 2014; Walker and Pavia, 2015), but a competitive insulation material must not only meet good thermal performance, but also good acoustic characteristics in terms of sound insulation and a low level of environmental impact and production costs (Al-Homoud, 2005; Jelle, 2011; Papadopoulos, 2005).

The analysis addressing the evolution of paper and cardboard products uses in construction and architecture revealed that one can talk about a history of paper and cardboard constructions. The history of the development of cardboard-based constructions can be divided into the following three distinct periods (Ayan, 2009):

1. The birth of cardboard construction prototypes, from 1944 to the early 1990s;
2. The work of the Japanese architect Shigeru Ban;
3. Development of contemporary prototypes in recent decades.

**Stage I**

The first house made of paper can still be admired today at the Paper House Museum in Rockport north of Boston in Massachusetts (USA) (Fig. 3*a*) (Dugger, 2009; https://www.paperhouserockport.com/). The house was built by the mechanical engineer Elis F. Stenman who designed office paper machines and was passionate about paper ("Elis F. Stenman started building his house in 1922 as anyone else would, with a timber frame, roof, and floors. But when this mechanical engineer and tinkerer began constructing the walls, he chose to use a decidedly different form of wood: newspaper....." (https://admire.social/place/17367)). The house was built between 1922 and 1924 and was used as a holiday home until 1930. According to the description of the museum's custodian - one of the builder's nieces, the house has a common structure, with wooden floor and ceiling, but walls with about an inch (2.54 cm) thick are made of layers of pressed newspapers glued together with glue and on the outside with varnish. This ensured good waterproofing and, as evidenced, the house has withstood well to this day. The custodian's comment does not show how the wall structure is maintained, but from the photos on the museum's website (http://www.paperhouserockport.com) one can see a wire mesh, probably the thickness of office clips, which ensures the stability of the walls outside. Inside, the furniture is made of paper.

A second known building, chronologically, made mainly of cardboard dates from 1944 and is constructed of 1 inch (2.54 cm) thick corrugated cardboard processed from waste and impregnated for stiffening with sulfur and fire retardant paints (Fig. 3*b*). The 1944 house was followed by a period of slow development in the field (Ayan, 2009).

One of the first architects to turn to cardboard as a building material was Richard Buckminster Fuller (1895-1983). He was not only a famous architect, inventor of the geodesic dome, but also a visionary, designer and environmental activist (Sekulic, 2013). His approach was based on a philosophy that combines environmentally sustainable construction concepts with sustainability and financial terms. Going further, he developed strategies to solve global problems based on his philosophy: ***more with less***. His philosophical conception is summed up in the term Dimaxion which he invented by combining the words: dynamic, maximum and tension, which he describes as meaning to do more with fewer resources, based on the principle that the whole is greater than the sum of its parts (Chu and Trujillo, 2009).

In order to keep the cardboard structures stable in the conditions of exposure to the external environment, humidity and fire, geodesic domes and other macropoliedric forms were developed and tested, considered, at one time, the best solution for this problem. The weather protection of these prototypes was achieved by applying substances such as boiled linseed oil, polyurethane paints, resin-based paints and fiberglass or concrete on the outer surface of the structure. Some of the structures made in this step are shown in Fig. 3(*c*-*i*). Despite efforts, these early prototypes have only passed the test of time as short-term and small-scale applications.

**Stage II**

In the second stage which started in the mid-1990s, cardboard experienced a new flowering as a material used in architecture and construction due to the achievements of the Japanese architect Shigeru Ban (b. 1957). Cardboard may seem like an inappropriate material to build in areas where natural forces have destroyed permanent homes, but the Japanese architect Ban has shown around the world that materials such as cardboard boxes and paper can be used to create temporary homes and social structures, which have a protective role and can be lifted quickly (Anon, 2014).

In his projects, Ban mainly used cardboard tubes as a structural element of the construction, often supplemented with many unique materials, but available at low cost in the area. In Fig. 4 a number of 25 of the works in which the architect used such building materials were selected. Ban can be considered an architect concerned with improving the lives of people affected by natural disasters. Thus, paper houses and beams were designed as emergency shelters following natural disasters in Japan (*a*), Turkey (*d*), India (*f*), Haiti (*p*) and the Philippines (*v*).

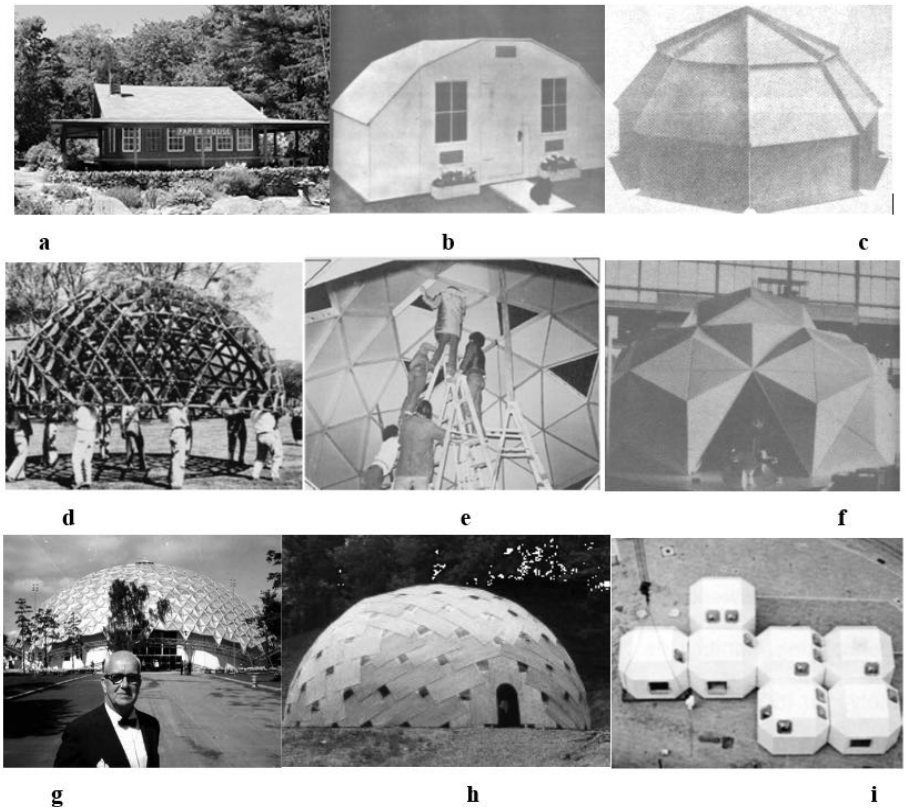


Fig. 3 – Examples of early cardboard constructions (Ayan, 2009): *a* – Rockport Cardboard House Museum (1922-1924); *b* – The cardboard house from 1944; *c* – emergency shelter built by Container corporation (USA, 1954); *d* – Geodesic paper dome coated with polystyrene resin built by Buckminster Fuller (Tulane University, 1954); *e* – The Charas Project assisted by Michael Ben Eli (New York, 1970); *f* – The stereometric dome of D.G. Emmerich & Jungmann (Wegwerf architecture exhibition, Paris 1970); *g* – Photograph of Buckminster Fuller in front of the geodesic dome built as the U.S. flag at the American Exchange Exhibit (Moscow 1959); *h* – The new generation dome built by S. Miller (1994); *i* – Casa-Nova project built by 3 H Architects (Munich Olympics, 1972).

The use of cardboard tubes is the common element, but the projects are adapted to correspond to the local specifics. Thus, for the foundation were used beer crates filled with sandbags in Kobe (Japan) or the remains of bricks resulting from demolition in India. In Turkey, better wall insulation was needed compared to Japan due to climate differences. Thus, in addition to a spongy tape with adhesive placed between the tubes of the walls, it was necessary to insert into the tubes some pieces of shredded paper that ensure a better thermal resistance. Fiberglass was also used to protect the ceiling and plastic and cardboard sheets according to the needs of the residents.

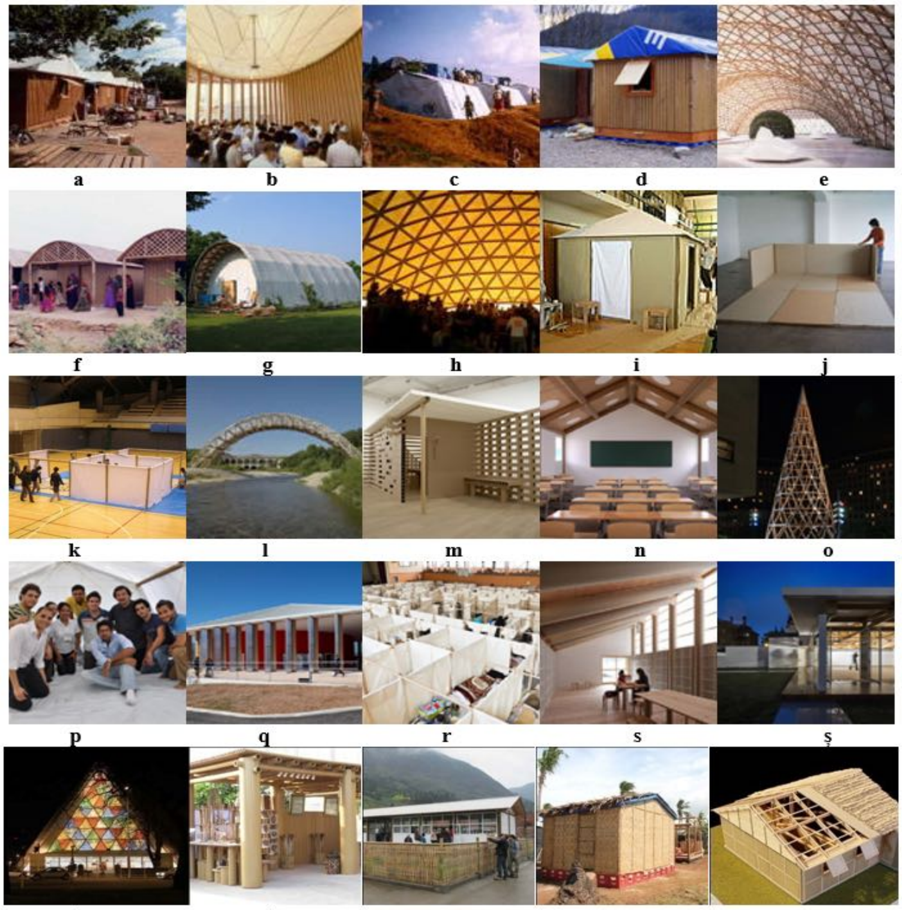


Fig. 4 – Constructions designed by the Japanese architect Shigeru Ban using as main materials cardboard tubes and paper (photos taken from the website http://www.shigerubanarchitects.com/works.html on 15.03.2017) *a* – paper (Kobe, 1995); *b* – the paper church (Kobe, 1995); *c* – paper emergency shelter (Rwuanda, 1999); *d* – Log and paper house (Turkey, 2000); *e* – Japanese Pavilion (Hannovra Exhibition, 2000); *f* – Beam and Paper House (India, 2001); *g* – The paper studio (Japan, 2003); *h* – Paper Theater (Amsterdam / Utrecht, 2003); *i* – paper house-Paper separation system in collective emergency shelters- (variant 1-2004); *j* – Paper separation system in collective shelters (variant 2-2005); *k* – Separation system in collective shelters (variant 3, 2006); *l* – The paper bridge (France, 2006); *m* – paper house for tea (2008); *n* – Hualin Temporary Elementary School (China, 2008); *o* – The Paper Tower, (London, 2009); *p* – paper shelters (Haiti, 2010); *q* – Paper Concert Hall (L'Aquila, 2011); *r* – Paper separation system in collective shelters (variant 4); *s* – Omagawa Paper Workshop (2011); and so on. Madrid Paper Pavilion (2011); *t* – Cristchurch Cardboard Cathedral, (New Zealand, 2013); tert. Abu Dhabi Art Pavilion, (2013); *u* – Yaan School of Nursing (2014); *v* – The House of Beams and Paper (Philippines, 2014); *w* – Nepal Project (2015).

In India the floor was covered with traditional clay, and the roof structure was built of whole bamboo tubes for the horizontal beams or sectioned for the other elements. Two layers of woven local cane mats were placed over this structure, including a plastic tarpaulin. Following the 2010 earthquake in Haiti, Ban built 50 shelters out of cardboard tubes and local materials for a minority group of victims (Latka, 2017). In the case of the typhoon in the Philippines in 2013, the houses for temporary shelters were built with foundations from beer crates filled with sandbags, and coconut wood and plywood were used for the floor. Woven bamboo mats were spread along the walls with the structure of paper tubes. The roof was constructed of Nypa palm leaves arranged over plastic sheets (http://shelterprojects.org/shelterprojects2015-2016/SP15-16_A8-Philippines-2013.pdf, Toshimasa and Masahiko, 2002).

In Nepal, following the 2015 earthquake, the Japanese architect used modular wooden frames from the windows of demolished houses (dimensions 90x120 cm) as a structure for walls, filling these frames with remnants of bricks also from demolished houses. This time the cardboard tubes were only used for the roof structure (Architectural Digest, 2016).In addition to shelters located in nature, Ban was also interested in creating systems to ensure the privacy of victims, by creating separate structures for their accommodation in collective spaces (schools, theaters and others). The architect continuously perfected these separation systems from the first variant in 2004 (Fig. 4*i*) passing through the second variants (Fig. 4*j*) and the third (Fig. 4*k*) from 2005 and 2006 to the fourth variant (Fig. 4*r*) conceived in 2011. In this last project, the structure is made of cardboard tubes from which the canvases that form the walls are fastened with safety pins.

In addition to emergency shelters, Ban used paper and cardboard for other larger buildings: Kobe Church (Fig. 4*b*) and Christchurch Cathedral, New Zealand (Fig. 4*t*), the Japanese pavilion at the exhibition in Hanover (Fig. 4*e*), as well as the Madrid pavilion (Fig. 4*ş*), the Amsterdam-Utrecht paper theater (Fig. 4*h*), the concert hall L'Aquila Italia (Fig. 4*q*) and the Abu Dhabi Art Pavilion (Fig.4*ţ*), the paper studio in Japan (Fig. 4*g*) or the paper workshop in Omagawa (Fig. 4*g*, 4*s*) as well as the temporary primary school in Hualin China (Fig. 4*n*) or the Kindergarten in Yaan, China (Fig. 4*u*). Also noteworthy are the Bridge of beams and paper over the Gordon River in France (Fig. 4*l*) or the paper tower in London (Fig. 4*o*), the tallest paper construction ever made (22 meters). Finally, in the Paper Tea House (Fig. 4*m*), the Japanese architect uses for the first time cardboard tubes with a square section (Fairs, 2018).

For his outstanding professional merits, Shigeru Ban was awarded the Pritzker Prize in 2014, the most prestigious award in the field of modern architecture (Reuters, 2014). In the motivation, the jury explained that this award was given to him for the innovative use of materials and his involvement in humanitarian actions around the globe.

Other architects also approached cardboard as a building material, some of them giving up cardboard tubes in their projects. Thus the house shown in Fig. 5 was built in Australia in 2004 by architects Stutchbury and Pape.

Fig. 5 – The cardboard house of architects Stutchbury and Pape (Australia, 2004); (source http://www.ecofriendlyhouses.net/cardboard-house.html, accessed 17.03.2020).

This achievement is, in fact, the result of a partnership between the firm of the two architects and a research unit at the University of Sydney (Paolella and Quattrone, 2007). The house proposes a cardboard portal structure with interconnecting cardboard walls and floor. Constrained by the limitations of the strength of the cardboard, the walls are inclined inwards to form a tent, and in the upper part, for space saving, the bedroom is located. The construction is wrapped in a protective film made of high density waterproofed polyethylene, and the ventilation can be achieved through large pivoting panels located on the north side (http://www.ecofriendlyhouses.net/cardboard-house.html). The house is made of 85% recycled materials, all materials being 100% recyclable and can be assembled by two people in about 6 hours.

Another project from this period is that of the cardboard building belonging to the primary school and the Westborough kindergarten in Westcliff on Sea (Great Britain) (Fig. 6). The building was designed by the architects Cottrell and Vermeulen and completed in 2001 (http://www.engagingplaces.org.uk/teaching%20resources/art67590). The basic construction elements are, this time, both the panels and the cardboard tubes. The tubes are used as structural columns, and the walls and roof are made of honeycomb-edged cardboard panels to allow the application of conventional interconnection methods.

Fig. 6 – Cardboard building for Westborough Primary School and Kindergarten in Westcliff on Sea (UK)
(source http://www.engagingplaces.org.uk/teaching%20resources/art67590 accessed 17.03.2020).

On the exterior walls there are printed instructions for the origami construction of a local bird species by artist Simon Patterson (https://www.ajbuildingslibrary.co.uk/projects/display/id/3679). The building was designed to last 20 years and cost £ 177,000.

**Stage III**

For the presentation of the third stage, only two projects were selected that exceeded the prototype stage and entered the market. It is, first of all, the Dutch model of the so-called *Wikkelhouse* ("wikkel" in Dutch means to pack) (https: //www.fictionfactory.nl/en/wikkelhouse/). This is, in fact, a flexible concept in which similar individual modules are interconnected to form a house, a commercial building, a showroom or an office (Fig. 7). The project was carried out by Fiction Factory, a company from Amsterdam, in 2015. The main material used in this concept is corrugated board processed from virgin cellulose fiber obtained from Scandinavian trees. The corrugated cardboard is rotated around a huge shape according to a method patented by RS Developments, adding an ecological adhesive. In this way a stable sandwich layer is formed, which also possesses good thermal insulation properties. The sandwich contains 24 layers of corrugated cardboard and is covered with a high-density polyethylene foil with the role of protection against moisture and the diffusion of vapor to the outside. The plywood on the inside comes from Chile, from the fast-growing conifer Arauco, and on the outside it consists of pine slats. The total thickness of the wall is 14 cm. Each module has a height of 3.5 m, a width of 4.5 m and a depth along which the junction between modules of 1.2 m is made. The usable area of a module is about 5 m$^2$ and weighs about 400 kg.


Fig. 7 – *Wikkelhouse* (package house) made of 24 layers of corrugated cardboard (Photos and information taken from http://www.fictionfactory.nl/en/wikkelhouse/ and http://www.wikkelhouse.com/ accessed on 18.03.2020).

The house can be built in one day and can be delivered with closed facades or glass facades. Due to its low weight, the building does not need a foundation, being placed on a chassis made of concrete legs and wooden beams. The house can be made of more or less modules depending on the desire of the tenant, but for a greater degree of comfort it is recommended to use at least five segments, some of which are specially designed for heating with a wood stove and chimney, another for kitchen and a third for the bathroom (Fig. 7).

*Wikkelhouse* was designed to last at least 50 years and after the completion of its life cycle is 100% recyclable. The price is about 25000 Euro for 3 segments excluding transport and installation costs. There is a high demand for such houses on the market, but the company makes only 12 houses each year, trying to maintain a high quality standard and customize the houses according to customer requirements.

Another success story of cardboard in construction is that of the Swiss company Ecocell, a private company based in Uttvil in the canton of Thurgau that deals with the planning and construction of residential properties, including modular eco-solar houses based on the implementation of construction elements, of the innovative Ecocell® system. The founder of the company is the entrepreneur and inventor Fredy Iseli, who has built over 250 properties and building complexes during his career. In 1989 he took over the packaging company Victor Traber AG, which became the starting point for the development and manufacture of innovative products based on recycled paper. The experience gained allowed the development and implementation of the Ecocell® modular construction system and the patenting of Ecocell® technology (https://www.detail-online.com/article/modular-homes-in-recycled-paper-28157/).

The Ecocell® construction system is innovative and inexpensive, being based on Ecocell® panels, which allow the dry construction of some residential properties, using a modular system of construction elements. The panels are made of the patented material under the name of Ecocell® Betonwabe® honeycomb concrete, whose dense structure gives it superior rigidity. The basic material for the Ecocell® modular construction system consists of untreated corrugated cardboard panels with honeycomb structure (raw honeycomb cardboard). These honeycomb-structured cardboard panels are manufactured exclusively for use in construction for Ecocell® Betonwabe® material and Ecocell® modular construction systems (Ecocell, 2016).

To make the Ecocell® Betonwabe® material, the raw honeycomb corrugated cardboard panels are uniformly covered with a layer of cement (concrete), so that their cellular structure remains intact. Then the dry elements are covered with wood panels. The sandwich composites thus formed are then processed into Ecocell® modular construction elements, which can be connected to each other by groove and spring systems. Advanced technology with computer-operated machine centers ensures high precision of the elements. Ecocell® modular construction systems include wall and ceiling elements, as well as various connecting and special-purpose components. Ecocell® has the advantage of high compressive strength, acceptable thermal insulation and the fact that it is a fireproof, environmentally friendly and lightweight composite material. Thus panels of this type have a high compressive strength combining the benefits of the rigid honeycomb structure with the advantages of concrete. This structure allows a compressive strength of up to 240 $t/m^2$ (24 $kg/cm^2$).

Regarding the thermal conductivity, it is quite low with a value λ = 0.13 W/mK, comparable to that of solid wood.Panels and walls of this type also offer a high degree of protection against fire. This is due to the cells covered with concrete and the closed structure provided by the construction of the wall in several layers. Another quality of these construction panels is that they are durable and environmentally friendly, being 100% renewable and recyclable. Finally, with a density of only 230 kg/m$^3$, Betonwabe® honeycomb concrete is about ten times lighter than concrete and about three times lighter than solid wood. Even large-scale Ecocell® wall and ceiling components can be manually lifted for assembly at the construction site (CMS, 2015).

The construction of Eco-Solar modular houses on several terraced and semi-detached properties started in the eastern part of Switzerland in the first half of 2016, thus marking for the first time the implementation of Ecocell® construction technology systems. Energy-optimized buildings produce their own energy, based on an advanced photovoltaic system, which covers part of the wall and facade. Arranged after glass, solar cells also provide high-quality thermal insulation (Brunthaler and Kemper, 2000). The autonomous decentralized solar power system generates more electricity than the household consumption of the residents. There are also thermal tanks that compensate for fluctuations in electricity consumption. As part of the innovative concept, an electric car is included for each household, ensuring mobility without air emissions.

## 3. Conclusions

In this work, an analysis of the relevant uses of paper and cardboard in construction and architecture was elaborated. It has been pointed out that there are a number of studies in the literature demonstrating the possibility that cardboard products with sufficient compressive strength can withstand structural loads, thus providing an alternative to the use of traditional building materials (concrete and steel), in construction and architecture. There is also the potential to use cardboard as a material in making assemblies such as construction elements, such as panels for walls, roofs and floors, as well as for the development of short-lived or temporary buildings. However, there are few studies that use cardboard waste for these purposes.

From the multitude of information selected from the literature, two projects that were beyond the prototype stage and entered the market were retained as significant. First of all, it is the Dutch model of the so-called *Wikkelhouse*, a flexible concept in which similar individual modules are interconnected to form a house, a commercial building, a showroom or an office. The main material used in this concept is corrugated board processed from virgin cellulose fiber obtained from Scandinavian trees. The project was carried out by Fiction Factory, a company from Amsterdam, in 2015.

Another significant successful project involving the use of cardboard in construction is that of the Swiss company Ecocell, which has proposed an innovative and inexpensive construction system based on Ecocell® panels. The basic material for the Ecocell® modular construction system consists of untreated corrugated cardboard panels with honeycomb structure (raw honeycomb cardboard). These cardboard panels with honeycomb structure are manufactured exclusively for use in construction.

From the presented results the potential of cardboard to contribute to the carrying out of more sustainable constructions is shown. Therefore, cardboard used in construction and architecture can perform better than expected, in terms of structural and fire resistance, and is relatively inexpensive in its raw form. In terms of environmental impact, the main goal is to use, as far as possible, recycled and recyclable materials.

The big challenge for cardboard is to overcome the double negative impact of fire and water resistance, without the use of other materials or additives that compromise the environmental benefits that come from the recycled nature of cardboard as a raw material. The options for achieving this are discussed below.

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# UTILIZĂRI ALTERNATIVE ALE HÂRTIEI ȘI CARTONULUI ÎN ARHITECTURĂ ȘI CONSTRUCȚII

(Rezumat)

În această lucrare s-a elaborat o analiză a utilizărilor relevante ale hârtiei și cartonului în construcții și arhitectură, ca bază de informații pentru studii și cercetări viitoare. În acest context, pe baza datelor din literatura de specialitate, se demonstrează că este posibil ca produse de carton cu o rezistență suficientă la compresiune să poată suporta sarcini structurale, oferind astfel o alternativă la utilizarea materialelor tradiționale de construcție (beton și oțel), în domeniul construcțiilor și în arhitectură. Există, de asemenea, potențialul de utilizare a cartonului ca material în realizarea unor ansamble ca elemente de construcție, cum ar fi panouri pentru pereți, acoperișuri și podele, precum și dezvoltarea unor clădiri cu durată scurtă de viață sau temporare.