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Cardboard Architecture. Eight Decades of Exploration in Academic Research and Professional Practice 1940-2019

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Abstract

Explorations in the use of cardboard products in architecture appear in the field's research literature since the 1940s. However, it was not until the early 1990s, when Shigeru Ban's work emerged, did cardboard products became a potential material for architecture. Since then, cardboard use in architecture has been continuously growing worldwide, and Ban's cardboard buildings have now achieved important recognition. This article is a review of cardboard architecture in academic research and professional architectural practice in the last eight decades. The article summarizes the fundamentals of cardboard architectural design and illustrates diverse strategies proposed by different authors to decrease cardboard strength degradation due to the material's weaknesses.

Keywords: cardboard architecture, sustainable architecture, recyclable materials, low-cost materials.

Introduction

This research surveys the history of scholarship and practice in cardboard architecture through a comprehensive and systematic review of research publications and architectural works covering the period of 1940 to 2019. The first cardboard research study was published in 1940[1] and the first significant architectural work using cardboard was from 1944[2]. The analysis describes a chronology of cardboard applications in architecture highlighting strengths, weaknesses, and application strategies developed by diverse researchers and designers.

This work is part of a research project that explores how to make building components for low-cost and sustainable housing with cardboard products (either brand-new cardboard or post-consumer cardboard) with special focus on its application in developing contexts. Cardboard is commonly underutilized in these settings where it ends up in landfills or dumpsters, wasting a valuable resource. The research aims to propose upcycling waste cardboard products into

[1] The first publication found from 1940 presents the results of a series of tests performed by the USDA Forest Service - Forest Products Laboratory to determine the resistance of resin-treated paper honeycomb core boards to humidity (Boller 1940).

[2] In 1944 the Institute of Paper Chemistry in the United States of America built an experimental shelter for emergency situations using paperboard panel system (J. F. Latka 2017).

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building materials for housing and respond to the growing demand for more sustainable construction materials. In these circumstances, cardboard products in architecture could be highly significant because they are easy to recycle, low-priced, and have relatively good strength to sustain loads, among other potential advantages for construction.

Although the interest in cardboard applications in architecture has been growing since the 1990s, thanks to the laureated Japanese architect Shigeru Ban with paper tubes and the contribution of research centers at universities, it is still very challenging for any architect to visualize how to use cardboard materials and the issues of designing and building with it. Consequently, this article revisits cardboard architecture works done in academic research and professional architectural practice in the last eight decades to lay a foundation for the research in question and to inform future work by other scholars and practitioners in this area.

The authors implemented a systematic quantitative approach and identified sixty-six relevant scholarly publications dated between 1940-2019 and assembled a survey of one-hundred-six buildings that used a cardboard product as a primary building component or as part of hybrid building systems and built between 1944-2019. The review's analysis was organized in four parts. In the first part (section 4.1), the authors proposed a chronology of cardboard architecture, outlining the four principal research approaches found. These approaches included fundamental or technical analysis, prototypical applications in architecture, technology development studies, and material overviews. The chronology accounts for the contributions were organized in two periods: studies between 1940-1976 (section 4.1.1) and studies between 2000 onwards (4.1.2).

The second part of the results (section 4.2) focused on prototypical applications in architecture. In this part, the authors target different exploratory or speculative studies using cardboard products primarily developed in academic settings. In this context, researchers and designers focused on designing, prototyping, and testing different applications of cardboard products in construction as a building material alone or within a system that combines several elements. The next part (section 4.3) includes all those studies focused on advancing the production methods and application strategies of cardboard components in architecture.

The last part (section 4.4) describes the cardboard structural systems identified in the review using a combination of three existing structure classifications — two of them particularly related to cardboard structures. This section also includes observations on complementary components to cardboard structures, especially joints, stiffeners, adhesives, and additives that also impact the buildings' overall strength.

The analysis highlights that most of the research studies and applications are about adapting existing cardboard materials found in the market or carboard materials produced on-demand by researchers and designers. Although the main focus is on newly manufactured cardboard materials, there are also examples of waste cardboard reuse for architecture as it is or with minimal intervention. The analysis also emphasizes cardboard construction issues and considers how previous researchers and practitioners dealt with the material's vulnerabilities.

Table 1. Keywords List and Databases.

Cardboard Architecture	Cardboard Structures	Cardboard Constructions	Cardboard Houses
Cardboard Recycling	Cardboard Reuse	Cardboard Building Materials	Cardboard Structural Performance
Cardboard Mechanical Properties	Cardboard Acoustic Properties	Cardboard Composite Structures	Cardboard Composite Panels
Shelter Construction			

Databases: Google Scholar, Science Direct, Web of Science, Cumincad, Google Patents, and the National Technical Reports Library

2. SCOPE AND METHODS

This study combined two sets of information about cardboard architecture in research and practice. The first set includes a selection of sixty-six scholarly publications realized between 1940 and 2019 that touched upon the use of cardboard products — mostly brand-new products — in architecture and construction as a building material itself or in combination with other building materials. The scope of the selected publications included investigations based on qualitative, quantitative, and mixed methods that focused specifically on cardboard products use for architectural applications only. Based on Pickering and Byrne (2014), a systematic quantitative approach was used to organize the selected works into different categories and analyze their content. The advantage of this approach lies in its comprehensiveness and simple replicability. To complement this, certain aspects of the literature was highlighted using a more traditional narrative-style method. Table 1 describes the keywords used to start the search and the databases consulted.

The second set of data is a survey of one-hundred and six case studies of buildings or prototypes of building components made from cardboard between 1944 and 2019. The case studies were retrieved from the selected publications. In these case studies, cardboard is either the primary building material or it is combined with other building materials to produce hybrid constructions. The case studies include full architectural systems of cardboard buildings of different programs — e.g., shelters, exhibition structures, pavilions, residential, commercial, and public buildings — or individual building parts made or cardboard materials — e.g., specific solutions for building components such as floor, wall or roof panels, tiles, columns, beams, trusses, or blocks. The survey attempts to inform us, in detail, about these case studies. For instance, identifying what type of cardboard products was used, application, and structural systems proposed.

3. RESEARCH QUESTIONS

A look into previous investigations helps to understand the motivations and challenges faced by designers, engineers, and builders for making cardboard components more durable and safer for architecture and structural engineering. The analytical foundation for the review prioritized three aspects of cardboard materials in architecture. First, what is the chronology of cardboard materials use in architecture? Answering to this question is important because it could help understanding motivations and challenges faced by previous architects, engineers, and builders when building with cardboard materials. The chronology does not intend to write the history of cardboard (and paper) materials use in architecture as this has been well covered (Latka 2017). Rather, the intention is to look at how researchers and architects dealt with material, structural, and design issues when working with cardboard and in what geographic context. The second aspect addressed in this work seeks to illustrate diverse research approaches implemented in cardboard materials studies for architecture. The third and last aspect touches upon existing building systems with cardboard components and examines their design principles and fabrication strategies. This knowledge will guide future designers when dealing with cardboard for architecture.

4. RESULTS

4.1 Chronology of Cardboard Architecture in Technical Research

This section depicts cardboard architecture's chronology by comparing the number of research publications about the subject and the number of constructed buildings that used cardboard products from 1940 until 2019. Essentially, only 11.76% of the publications in this area are from the period 1940-1976, and the rest from the year 2000 onwards. Figure 1 illustrates this relationship. This graph shows the relatively low production throughout six decades from 1940 until the late 1990s and into the early 2000s. The emergence of Shigeru Ban Architects (SBA) paper buildings in the 1990s and the subsequent establishment of university research centers focused on research and development of cardboard applications in the construction industry motivated the growth in the number of publications and prototype buildings.

These research centers have substantially impacted the increasing number of publications (83.58% of all items correspond to academic centers). Several studies in cooperation with industry, military, and government institutions, mostly in North America and Europe, made possible significant advances in developing cardboard technologies for architecture. The review identified five key academic centers: a) Cardboard Technical Research and Developments at TU Delft — almost 23% of all publications are from this center; however, it is no longer active; b) the BAMP

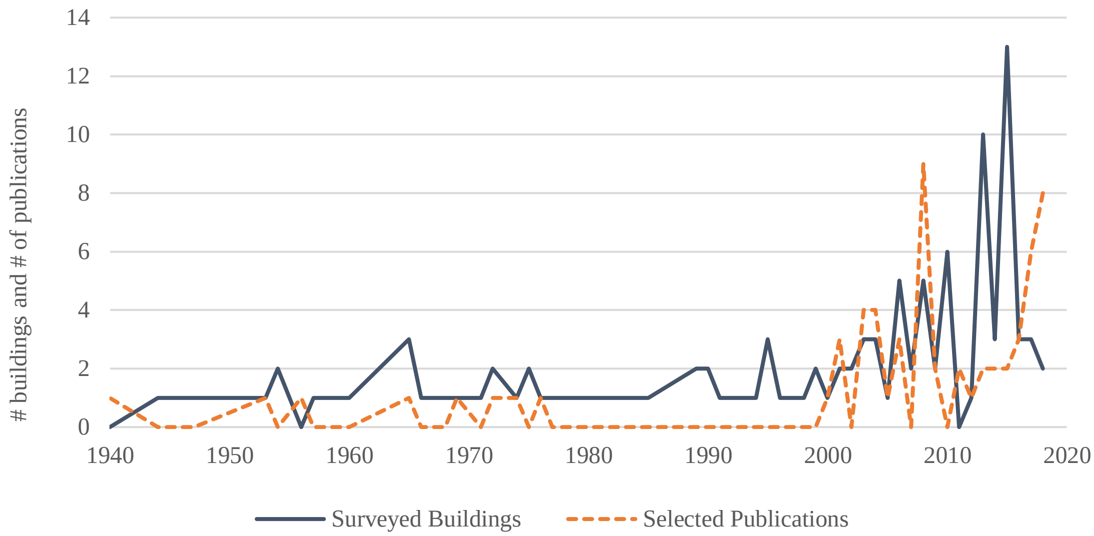


Figure 1. Cardboard Architecture in Research and Practice. Adapted from (Diarte, Vazquez, and Shaffer 2019a).

Building with Paper Project at TU Darmstadt — the project initiated in 2017 and has made several publications, five of them are part of this review; c) Radical Reuse of Waste for Architecture project at Penn State University — the project started in 2016 and has published five research items so far; d) Cardboard in Architectural Technology and Structural Engineering (CATSE) at ETH Zurich — this group is no longer active but has contributed substantially to the field. Of the remaining publications, a substantial part (almost 12% of the total) corresponds to the Buro Happold Engineering Company (five items) and SBA (three items).

Table 2 groups all selected publications in four primary research areas: fundamental or technical analysis, applications in architecture, cardboard technology for architecture, and cardboard architecture overviews. The first three are based on the categories proposed by Eekhout (2018a, 3), who co-led the study of cardboard in architecture at TU Delft during the 2000s. The last was added to include crucial publications that offer cross-sectional observations of cardboard architecture and related subjects in different geographical contexts.

Experimental studies about the material properties of carboard elements make almost 42% of all selected publications. The most recurrent themes are structural performance under different types of loads at short and long-term action (principally axial and transverse compression, impact, bending stress, creep fracture, and wind loads). Other themes include moisture absorption, water resistance, strength improvement strategies, thermal conductivity, acoustic absorption performance, material structure analysis of cardboard composites, flammability, combustibility, smoke, fireproofing, and durability. The novelty of cardboard elements in architecture and the lack of data for its use in construction are the main reasons researchers have extensively addressed this research area. The following section describes the main trends found in these studies.

4.1.1 Early Publications on Cardboard Research

The publications between 1940-1976 focus on structural performance, durability, thermal and moisture resistance of composite walls and portray the researchers' perspective regarding the potential of these "new" materials for construction. Figure 2 shows the configuration of composite panels proposed by these groups of publications. The work developed by Boller (1940) and Seidl (1956), for instance, was part of a five-year-long project that aimed to assess honeycomb boards' durability in the construction of shelters. Similarly, Buxton (2013) studied “sandwich materials” for the development of military shelters. These researchers employed resin-treated honeycomb boards, which helped decrease moisture absorption — in combination with aluminum and plywood facings and bonded with phenolic resins. The resins contained formaldehyde, which is highly toxic

Table 2. Research focus and correspondent publications

Research Focus	Selected Publications
Fundamental or Technical Research (Total = 29)	(Kiziltoprak 2018), (McCracken and Sadeghian 2018), (Lübke et al. 2018), (Gerusa de Cassia Salado and Dias 2018), (Schütz 2018), (Buckley et al. 2017), (Buratti et al. 2016), (Asdrubali et al. 2015), (Gerusa de Cássia Salado and Sichieri 2014), (Van der Meer 2013), (Sekulic 2013), (Preston and Bank 2012), (Doremus and Moody 2011), (Gerusa de Cássia Salado 2011), (Pohl 2009), (Schönwälder and Rots 2008), (Schönwälder, Van Zijl, and Rots 2006), (Dweib et al. 2006), (Correa 2004), (Cripps 2004), (Schonwalder 2004), (Dweib et al. 2004), (McQuaid 2003), (D'Costa and Bartlett 2003), (El Damatty, Mikhail, and Awad 2000), (Worrel and Wendler 1976), (Greene et al. 1972), (Buxton 2013), (Seidl 1956), and (Boller 1940).
Applications in Architecture (Total = 42)	(Diarte, Shaffer, and Obonyo 2019), (Diarte, Vazquez, and Shaffer 2019a), (Diarte, Vazquez, and Shaffer 2019b), (Morales-Beltran, Eigenraam, and Latka 2019), (J. Latka 2019), (Kanli 2018), (McCracken and Sadeghian 2018), (Diarte and Shaffer, 2018), (Lübke et al. 2018), (Schütz 2018), (Schütz 2017), (Ban 2017), (J. Latka 2017), (J. F. Latka 2017), (Shah 2017), (Gattas and You 2016), (Portheine 2015), (Imperadori, Salvalai, and Pusceddu 2014), (Gerusa de Cássia Salado and Sichieri 2014), (Auslender, Biesalski, and Schabel 2014), (Van der Meer 2013), (Preston and Bank 2012), (Gerusa de Cássia Salado 2011), (Ayan 2009), (Pohl 2009), (Gentenaar 2018), (van Kranenburg, van Dooren, and Veer 2008), (Taco van Iersel and van Dooren 2018), (Eekhout 2018b), (Winandy et al. 2006), (Lin 2005), (Correa 2004), (Cripps 2004), (Dweib et al. 2004), (TM van Iersel 2003), (Ban and Shodhan 2003), (Cripps 2001a), (Cripps 2001b), (Dickson et al. 2001), (Sheppard, Threadgill, and Holmes 1974), (Thorpe 1965), and (B. Fuller 1953).
Technology Development (Total = 15)	(Diarte, Vazquez, and Shaffer 2019a), (Diarte, Vazquez, and Shaffer 2019b), (Kanli 2018), (Schütz 2018), (Schütz 2017), (J. F. Latka 2017), (Shah 2017), (Ayan 2009), (Eekhout 2018a), (van Doren and van Iersel 2018), (Gribbon and Foerster 2018), (Taco van Iersel and van Dooren 2018), (Schönwälder, Van Zijl, and Rots 2006), (Cripps 2004), and (B. Fuller 1953).
Reviews (Total = 9)	(Bach et al. 2018), (Schütz 2018), (Ban 2017), (J. F. Latka 2017), (Bank and Gerhardt 2016), (Ayan 2009), (van Doren and Verheijen 2018), (Gribbon and Foerster 2018), and (Cripps 2004)

and considered today a non-environmentally friendly product.

Moreover, Greene et al. (1972) tested honeycomb boards for a roof, ceiling, and floor components. The configuration of their components varies in thickness and the number of carboard layers employed. They also introduced gypsum boards as fire protection and fiberglass laminates to reinforce panels' strength. The last example by Worrel and Wendler (1976) included thermal conductivity analysis of three and five layers of honeycomb core sandwich panels. Although they did not find a significant improvement in the boards' performance with the addition of different layers, they did improve the cardboard's fire endurance.

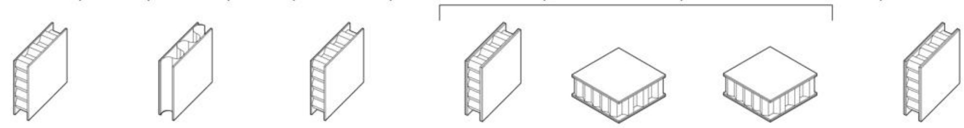
Overall, these research endeavors conclude that the carboard was still inferior to timber construction. The studies demonstrated that cardboard products' durability under long-term exposure to loads and natural elements was one of the researchers' main concerns. Consequently, other composite panels made from more durable materials such as aluminum, plywood, and plastics combined with foam — for its high thermal and acoustic characteristics — were preferred for building shelters instead of cardboard products.

4.1.2 Cardboard Research from 2000 Onwards

Studies in this period stated positive results for cardboard products as structural components, mostly corrugated cardboard, paper tubes, honeycomb boards, and cardboard profiles (Lübke et al. 2018; Gerusa de Cassia Salado and Dias 2018; Latka 2017; Gerusa de Cássia Salado and Sichieri 2014; Van der Meer 2013; Ayan 2009; Dweib et al. 2006; Correa 2004). Some studies explicitly remarked that some of these materials are viable for "strong, stiff, and lightweight structures" (McCracken and Sadeghian 2018; Gattas and You 2016; Gerusa de Cássia Salado 2011). Nevertheless, concerns about failures in paper tube shell structures due to large bending moments, compression forces, and the lack of standardized construction guidelines for paper products (Shah 2017) remained among researchers. Three seminal references highlighted considerable effects of creep (change in dimensions in the structural element caused by stress) and relative humidity on cardboard products' strength as the most critical factors to make it a suitable material for construction (Eekhout 2018b; Correa 2004; McQuaid 2003).

Corrugated cardboard is one of the most popular cardboard products. Corrugated cardboard is a sandwich structure composed of three carboard elements: two facings (liners) and a core (fluting). Cardboard is a composite, non-uniform (every tree offers different fibers), hygroscopic (highly porous material), and anisotropic (different values when measured in different orientation) material produced mainly with cellulose fibers that align in two directions forming plates (Latka 2017). Cardboard is also known as paperboard or board. The Machine Direction (MD) and Cross Direction (CD) refers to the machine with which the cardboard plate is produced. Generally, the MD has better tensile and compressive strength than the CD and usually aligns to horizontal loads because packaging containers (boxes) are highly exposed to lateral loads. In contrast, the CD frequently aligns with vertical loads (Hahn et al. 1992). This is not the case for parallel or spirally wound paper tubes — common in SBA's buildings — but it could be critical for panel structures. In this situation, incrementing the number of corrugated cardboard sheets could create more resistant plate components.

The question of how to strengthen cardboard products stands as a prominent concern. According to Eekhout (Eekhout 2018b), using cardboard products made of raw resources instead of recycled materials can add extra-strength to cardboard products. Also, the selection of adhesive type could have a considerable impact on the strength of the cardboard components. For example, using melamine resins instead of water-based adhesive would give extra-strength to the joining of layers and structuring of the material. Conversely, this product would make any architectural component "impossible" to recycle (Eekhout 2018b, 155). Increasing the resin content in the composition of cardboard products is a strategy highlighted by, for example, Doremus and Moody in



	(Boller 1940)	(Seidl 1956)	(Buxton 1969)	(Greene et al. 1972)			(Worrel 1976)
Panel Type	Three-layers	Three-layers	Three-layers	Three/Five-layers	Three/Five-layers	Three/Five-layers	Three/Five-layers
Application	Wall	Wall	Wall	Wall	Roof/Ceiling	Floor	Wall
Thickness	60 mm (2-3/8 in)	25, 50, and 75 mm (1, 2, and 3 inches)	12, 25, and 50 mm (1/2, 1, and 2 inches)	110 mm (4 1/4 in)	185 mm (7 1/4 in)	185 mm (7 1/4 in)	75 mm - 110 mm (3, 4 1/4 inches)
Core	Honeycomb Board Kraft Paper 7/16 in hexagon cells Resin-trated with 35% phenolic resin	Corrugated cardboard Resin-trated with 15% phenolic resin	Honeycomb Board Untreated natural kraft and Resin-trated with phenolic resin, or water and fire resistant polymers	Honeycomb Board (3 inches)	Honeycomb Board (6 inches)	Honeycomb Board (6 inches)	Honeycomb Board (6 inches)
Facing	6 mm thick plywood yellow popler 1.6 mm thick Alclad aluminum 7075	1/4 in, 1/10 in plywood 1/8 in veneer w/ paper overlay 1/4 in, 1/8 in tempered hardboard	Aluminum 2024 T-3	5/8 in Gypsum board (fire protection) + FRP Fiberglass woven roving cloth (strength reinforcement)	5/8 in Gypsum board (fire protection)	5/8 in Gypsum board (fire protection) + 5/8 in Plywood for the walking surface + FRP Fiberglass woven roving cloth (strength reinforcement)	0.7 mm Aluminum or 26 gauge Steel and 1/8 inches tempered hardboard as backup panel
Adhesive	Phenolic-polyvinil butyral adhesive	Phenolic resin Urea resin Sodium silicate	Liquid epoxy	Hot melt adhesive	Hot melt adhesive	Hot melt adhesive	Contact adhesive, neoprene, or thermo setting
Comments on results	"The aluminum-faced panels consistently show the highest compressive strength" (pag. 6)	"No visible signs of deterioration after 5 years. Stiffnes equal or greater" (pag. 22)	"Adhesive problems were indicated when panel samples were subjected to thermal stresses" (pag. v)	Mechanical tests demostrated failures as shearing separation between the gypsum board and the FRP laminate. However, the gypsu contributes to the structural resistance	"The test results indicate some sensitivity to humidity and a general tendency for the deflection to increase with increasing moisture content" (pag. 16)	"An increase in the RH cause a decrease in deflection, since the plywood on the upper compression surface increased in volume with increasing RH" (pag.16)	The fire test showed the addition of a layer of material between metal exterior skin and honeycomb core significantly increased the panel resistance. The thermal test showed the five-ply do not afford any avantage

Figure 2. Composite panels that incorporate cardboard products found in academic publications between 1940-1976. Source: Authors

(2011) when testing composite panels with honeycomb boards and magnesium and cement-based boards as facing as a potential alternative for building shelters in Haiti after the earthquake in 2011. Similarly, Salado (2011) reported a considerable increase in paper tubes' strength when impregnating paper tubes with a resin-based coating.

To increase shear and compressive strengths, other authors in this survey suggested pre-stressing the paper products before their use in construction to “activate all fibers segments inside the material” (Sekulic 2013, 42); however, this strategy has not been proven yet. Another strategy for improving structural performance is by impregnating cardboard with a cement-based plaster. Following this approach, Pohl (2009) experimented with impregnating honeycomb boards with a high-strength Portland cement-based plaster to increase strength and decrease moisture absorption and fire vulnerability. Pohl soaked honeycomb cardboard samples in high-strength plaster with a 1% addition of superplasticizer and demonstrated this technique doubles the material's compressive strength, decreasing moisture absorption by 80%, making the cardboard component "quasi non-combustible" (Pohl 2009, 170). This impregnation method's downside is that the cement increases the honeycomb boards' thermal conductivity and decreases its recyclability. Nevertheless, the thermal conductivity issue could be solved by adding layers to protect the boards from direct contact with heat sources. Figure 3 illustrates some examples of cardboard-core sandwich panels developed from 2000 onwards, describing the composite panels' main components.

Another critical issue of cardboard products is how to increase their resistance to moisture. In this sense, researchers had investigated the potential application of industrial by-products to create renewable additives for improving the water-resistance of paper composite materials. For example, Buckley et al. (2017) tested adding stearate salts, a by-product of the meat processing industry, into the carboard pulp and determined an increase of water resistance of over 900-fold. In a similar approach, Bertaud et al. (2012) tested using pulp mill residues to reduce or replace petrol-based chemicals to fabricate fiberboards. Overall, moisture resistance (addressing the environmental factors of rain and snow, atmospheric conditions of humidity) is a critical issue that must be solved to scale-up the application of any cardboard product in building construction.

Besides composite panels, paper tube structures for columns and arches stand out in the literature. For example, McQuaid and Ban (2003) published the mechanical characterization tests of paper tubes for several buildings designed by SBA. They employed paper

	(McQuaid 2003)	(Dweib et al. 2004)	(Cripps 2004)	(Pohl 2009)	(Salado 2009)	(Doremus and Moody 2011)	(Lübke et al. 2018)
Carboard Product	Honeycomb grid core panels	Paperboard	Paperboard and honeycomb panels	Honeycomb panels impregnated with high-strength cement	Paper tubes	Honeycomb panels	Honeycomb panels
Application	Structural beams	Structural beams for roofs	Structural panels for Walls and roof	Structural and thermoacustic wall panels	Structural wall panels	Structural wall panels	Structural wall panels and facade components
Thickness	18.3 mm	89 mm	200 mm	300 - 450 mm	100 mm	50 - 100 mm	45 mm
Core	Honeycomb Board	Elfoam T300 Foam, e-glass fiber, flax fiber as reinforcement	4 x 4 mm paperboard and 3 x 50 mm honeycomb board	250 mm thick honeycomb panel w/ 15mm cell size.	100 mm thick paper tubes with 5 mm wall thickness	47 mm thick panel high resin content and 75 mm thick panel with low resin content	40 mm honeycomb bard
Facing	0.8-1.4 mm Paperboard and plywood	Paperboards made of recycled paper and feathers, recycled paper with corrugated paper, and recycled paper and fiberglass	16 mm fibreboard cement panels Interior poly-coated layer protection for moisture and waterproof paper outside	10 mm Plywood, vapor barier, timber cladding. Gypsum fibreboard adds fire proofing	The surface was waterproofed with polyurethane resin	10 mm fiber reinforced magcrete board	2 mm semi-tempered-glass
Adhesive	N/D	Soybean oil based resins with natural fibers as reinforcement	N/D	N/D	N/D	The kraft paper was saturated or coated with with formaldehyde	Sodium silicate
Comments	“Average tensile strength was 105 kgf/cm2” “Average compressive strength was 94.5 kgf/cm2” (pag. 81)	The authors compared the strengths and stiffness of the composite beams made from recycled paper have strengths with conventional wood components. Their results show composite beams are suitable fo construccition (pag. 156)	“cardboard can work as a building material and has the potential to be a component of low environmental impact construction” (pag. 217)	“In exterior sandwich walls, the honeycomb core can be used either as a structural element only or as fulfilling structural and thermal insulation functions simultaneously.” (pag. 218)	The panels supported between 5000 kgf and 6000 kgf depending on the use of a coating resing or not. This results are acceptable for construction in Brazil (pag. 166). The panels also showed positive results to impact tests (pag. 171).	The researchers recomended not using these panels as structural components in high temperature and humidity environments. They recomended to replacing the magcrete boards and increase the amount of resins prior to its application.	The panels showed a high tensile strength and the authors built a pavilion using the glass-cardboard composite as a beam.

Figure 3. Cardboard-core sandwich panels found in academic publications form 2000 onwards. Source: Authors

tubes as columns and truss members for shell structures. Correa (2004) complemented this information by detailing experiences in other temporary buildings designed by SBA using the same material. Lastly, Preston and Bank (2012) experimented with paper tubes bending limits to engineer a "large temporary outdoor sculpture" with several paper tube-arches of different dimensions. Overall, these publications help understand some cardboard elements' mechanical properties for structural design, especially for its use as composite panels and shell structures.

4.2 Applications in Architecture

From the selected publications, 63.24% correspond to applications in architectural situations. These studies target different exploratory or speculative studies using cardboard products in academic and scientific settings (83.82%) or real-life applications in buildings (11.76%). Researchers following this approach focused on designing, prototyping, and testing in different ways, a variety of forms of cardboard products as a building material alone or within a hybrid system. Other aspects included in these publications are the design and fabrication of joints — either made of cardboard or other materials — disassembly, and recycling strategies.

Almost 60% of the investigations focused on the fabrication of composite panels for load-bearing and non-load-bearing walls, floors, or roofs/ceilings in this area. The panels combine corrugated cardboard sheets or honeycomb boards as core materials either with timber or aluminum framing and different facings for protection against the elements — e.g., steel, aluminum, glass, fiberglass, or gypsum boards. Remarkably, this application has been constant since the 1940s, either for use in the construction of conventional buildings or more specialized architectural forms, such as geodesic domes. Other applications include columns, arches, and concrete formwork or prototypes of joints for cardboard structures. A quarter of these architectural application experiments include fundamental or technical research, mainly to test the cardboard's structural performance. Universities played a leading role in producing prototype applications and corresponding publications, especially those focused on architecture, design, and engineering.

Figure 4 shows the diversity of typologies and cardboard products found in the buildings' survey. The public buildings category, which entails 22% of the total number of buildings, demonstrated the diversity of typologies, including schools, nurseries, churches, museums, theatres, and galleries. Generally, cardboard buildings involve low-rise constructions (3-5 m height) with short-span structures. The built area of cardboard buildings ranges from 10 m² for experimental pavilions and small exhibitions to 500 m² for buildings addressing temporary exhibits, shows, religious, or cultural events. Lifespan wise, 82.8% of the surveyed buildings were temporary constructions lasting a few weeks to months, and 22.8% of the total number of buildings were related to emergencies meant to last a few months. However, there are remarkable examples of long-span structures dedicated to host events of longer duration (the Japan Pavilion in Hannover 2000 lasted a year) or even semi-permanent activities (the Cardboard Dome in The Netherlands, erected in 2003, lasted around nine years). A few examples of permanent buildings (the Paper House by SBA was built in 1995 and still stands, the Wikkelhouse has an expected life cycle of at least fifty

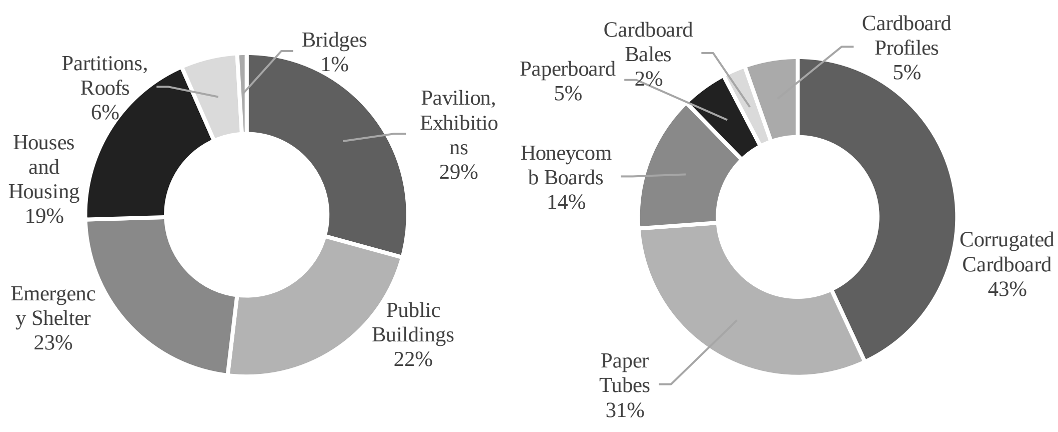


Figure 4. Application of Cardboard Products by Type of Building and Product.

years). Concerning the type of cardboard products used in these buildings, the same graph shows corrugated cardboard plates, honeycomb boards, and paper tubes are the most recurrent cardboard materials found in the buildings' survey.

Regarding the geographical location of case studies of cardboard buildings, the review reveals that 52.4% of the surveyed buildings are in Europe, 23.8% in North America, 16.1% in Japan, and a few case studies in Africa, and South America. Overall, two groups constitute essential references regarding the materialization of cardboard buildings. The first, SBA, designed almost 30% of the buildings, and the second group, which includes researchers and designers related to the TU Delft, developed 24.5% of the buildings. However, cardboard buildings' geographical location does not connect to specific climatic conditions (there are cardboard buildings in either cold and warm places) but to the existence of research centers at prominent design schools (e.g., TU Delft) and design offices (e.g., SBA). In some cases, the support of paper companies that seek to extend the market of paper and cardboard products has been critical to the development of cardboard technologies. Another essential aspect that factors in this tendency is related to the interest to develop sustainable alternatives for construction, which in the case of European countries is highly influential. So far, all these cardboard materials mentioned above come from the packaging industry. Still, designers and manufacturers adapted for their application in architecture.

4.3 Cardboard Technology Development

This section includes all those studies focused on advancing the production methods and application strategies of cardboard components in architecture. The area touches upon aspects like cardboard technology principles for research and design where researchers had to invent or adapt basic structural knowledge from similar geometries to an unknown material for construction. Buckminster Fuller (1953; 1965), for example, implemented the use of laminated corrugated cardboard panels for the geodesic domes. He also invented and developed a system for designing the geometry and constructing the domes. Eekhout (2018a), on the other hand, adapted existing space frame technologies and nodal designs for the development of similar constructions but with paper tubes. The same author also stated principles for future structures using paper tubes for engineering design and delved into commercial systems and product development principles. Similarly, Ayan (2009) investigated and proposed strategies for increasing people's acceptance of paper components in housing construction to extend the market of paper products.

Moreover, other researchers concentrated on developing prototype building materials and their methods and tools for design and fabrication. In this sense, some works devised computational models for predicting cardboard products' behavior during the design phase (Schönwälder, Van Zijl, and Rots 2006). Others explored the geometrical logic of folded structures and digital design and fabrication tools for developing parts with sheets of corrugated cardboard or paper tubes using both analogue and digital strategies (Schütz 2017; Taco van Iersel and van Dooren 2018; Gribbon and Foerster 2018; Diarte, Shaffer, and Obonyo 2019; Diarte, Vazquez, and Shaffer 2019a; 2019b). Some of the components developed include composite panels, structural framing, or concrete formwork. Materials and methods for joints and connections of cardboard parts are other aspects that have received attention lately, especially wood joint design and performance (Kanli 2018). A few of these investigations developed characterization studies of cardboard materials; however, most of them based their explorations on the literature results mentioned before. Overall, this group makes around 20% of all the selected publications, and the research centers on cardboard architecture stand out as the main contributors.

4.4 Cardboard Structural Systems

This section illustrates and describes cardboard structural systems found in the building's survey and organized using three existing structure classifications. The first is Engel's general classification of structural systems, namely *active surface structures* and *active vector structures* (1968). According to Engel, in *active surface structures*, all or part of the structure area is subject to shear loads, compression, or tensile forces. Translated to cardboard components, the bonding between the different layers that create the surface is critical for stability and durability. On the other hand, active vector structures are formed by linear elements with a small cross-section area that works appropriately for either compression or bending stresses. In these structures, the bracing, nodes, or joints have an essential role in the structure's stability. A second classification is proposed by Latka (2017, 495) includes three structural systems: a) *panel or plate*; b) *rods or frame*; and c) *dome or shell*. Following

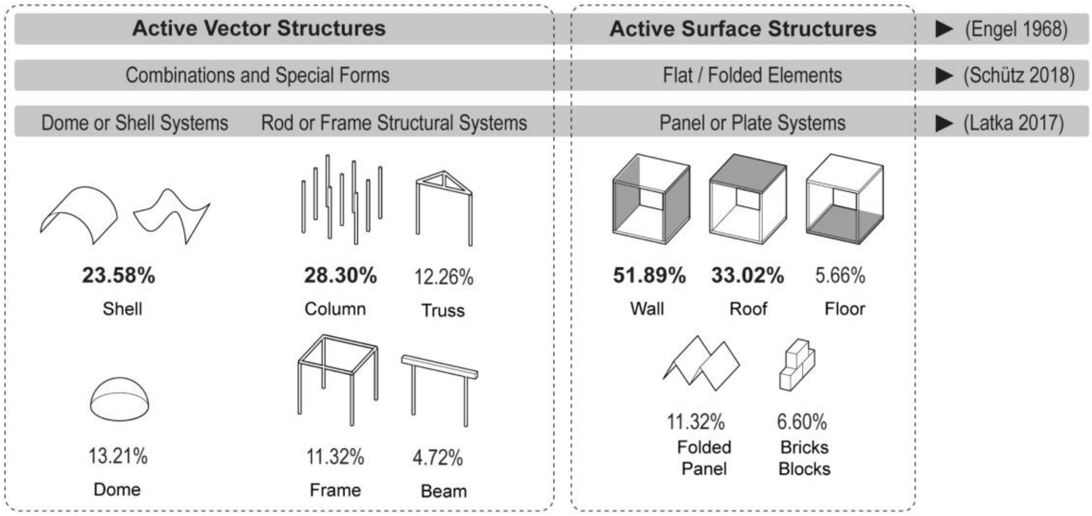


Figure 5. Cardboard structural systems classification. Source: Authors

Engel's approach, the system (a) is an *active surface structure*, and the systems (b) and (c) are *active vector structures*.

Similarly, Schütz organized part of his study of cardboard structures by a) *form* and b) *construction principles*. The classification (a) includes "*flat elements, folded elements*, and *combinations and special forms*" (Schütz 2018, 150). Each item in this classification implies a different construction principle. The *flat elements* include *shell, frame*, and *plate* construction principles (this is similar to Latka's classification). The folded elements include *free folded facades, dynamic folded facades*, and *parallel folded facades*. Lastly, *combinations* and *special forms* include *folded straps, assembles tubes*, and *folded frames*. Most studies implemented more than one structural system in different parts of the building. Figure 5 summarizes the classification of structural systems and highlights the incidence of each one in the survey.

4.4.1 Active Surface Structures – Panel or Plate Systems

Most of the examples of cardboard architecture found in research and practice fall into panel or plate systems. The most common applications in this category include wall panels, roof, or ceiling panels, and there are a few examples of panels for floor systems as well.

Almut Pohl's investigation (2009) about honeycomb boards for panelized constructions, for instance, proposed four different configurations for load-bearing walls and another six for non-load-bearing walls for low-rise residential and commercial buildings. Figure 6 illustrates the four versions for load-bearing walls using corrugated paper honeycomb boards of thicknesses 400 mm, 250 mm, and two of 120 mm. All these boards were impregnated with high-strength cement plaster to increase fire and humidity resistance. The design criteria include structural, thermal, sound, fireproofing, weight, and impact resistance requirements. The results showed promising and low-cost techniques for decreasing moisture vulnerability and strength loss in humid environments while maintaining the eco-friendliness of the material. The panels used honeycomb board as the structural and thermally insulating material, suggesting that no additional insulation material for the wall panels was required. The design is efficient because it integrates conventional vapor barriers, cladding elements, interior finishes, and excellent potential for large-scale production. Unfortunately, this review did not find any case of practical application to assess its results.

The next example of a panel system can be found in work developed by Ayan (2009). This system used corrugated cardboard sheets instead of honeycomb boards. This solution was based on Pohl's structural analysis developed as part of the CATSE team at ETH Zurich. In this example, Ayan proposed seven different types of wall components using several layers of corrugated cardboard sheets with the flutes in different directions — either parallel or perpendicular to

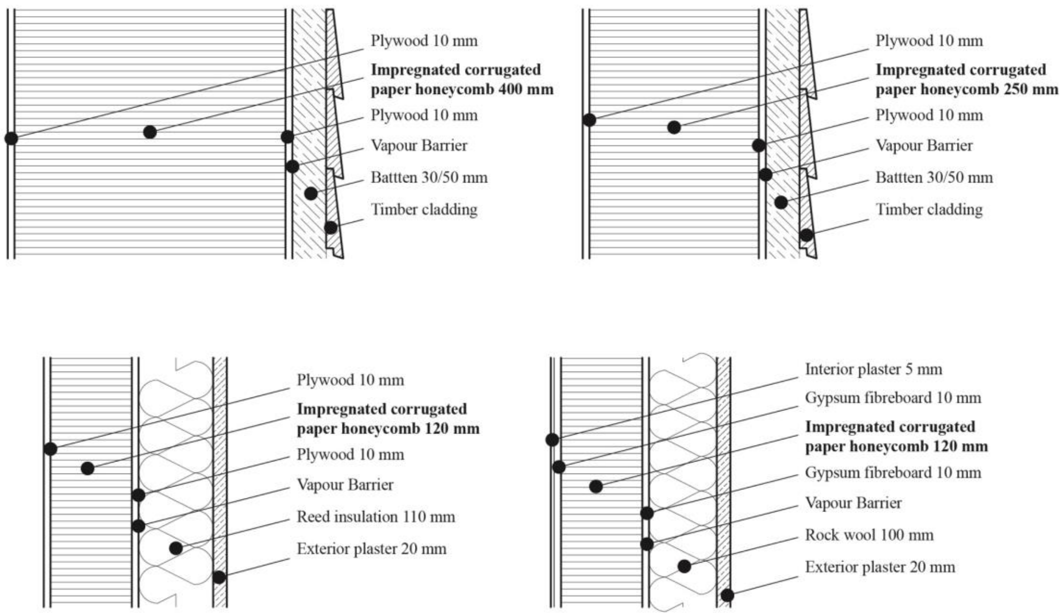


Figure 6. Examples of load-bearing wall using corrugated honeycomb proposed by Almut Pohl. Source: Almut Pohl

the ground. The panels' thickness varies from 50 mm for non-load bearing walls to 100-200 mm for load-bearing walls. Figure 7 shows prototypical wall-floor cardboard panels joints for a two-story building. Ayan assessed each wall's performance and proposed different categories: *form-active, thermal, easy, impregnation, structural, humidity, fire*, and *sound*. These “multifunctional cardboard composite wall components” can be easily mass-produced and rapidly constructed and include the structural, thermal, and acoustic requirements with a minimal design. Ayan suggested this multifunctionality concept could decrease weight, labor, and joints but preserve "quality and performance.” To complement these composite panels, the researcher proposed various surface finishes and considered different joining methods and adhesives. The panel's performance assessment followed criteria such as ease of manufacturing, impregnation process, structural performance, moisture, fire, and sound resistance.

Regarding examples in practical applications, two case studies stand out from the survey: the *Wikkelhouse* (Fiction Factory n.d.) and the *Open Source: Cardboard Pavilion* (Schütz 2014). These two cases stand out because they synthesize systematic technical research on materials, a comprehensive experimental construction process, and developed a customized technology for design and fabrication. Also, in both cases there was a meaningful collaboration between academia and industry making them outstanding precedents for future developments in cardboard for architecture.

The Wikkelhouse is a modular construction system of segments made from plywood frames and laminated plates of corrugated cardboard sheet — 24 layers of 5mm thick sheets with a total panel thickness of 120 mm — wrapped around the frame for producing a continuous panel for the wall, roof, and floor. Figure 8 shows a picture of the module fabrication process and a view of a building module in two stages: the finished module with a vapor barrier and one with the uncovered corrugated cardboard wrap. The Wikkelhouse, fully functional and commercially available, is a noteworthy example of hybrid construction that combines approximately 70% of corrugated cardboard and 30% plywood in volume. This laminated cardboard/plywood structure is entirely prefabricated using a highly sophisticated wrapping system, transported in modules, and assembled on-site via handling cranes. Figure 9 illustrates the typical cross-section of the envelope of the building. In this example, the structural system includes the wood frame, the interior and exterior facings, and the laminated plates of corrugated cardboard “filling the gap” between the frames. The layered plates also act as the

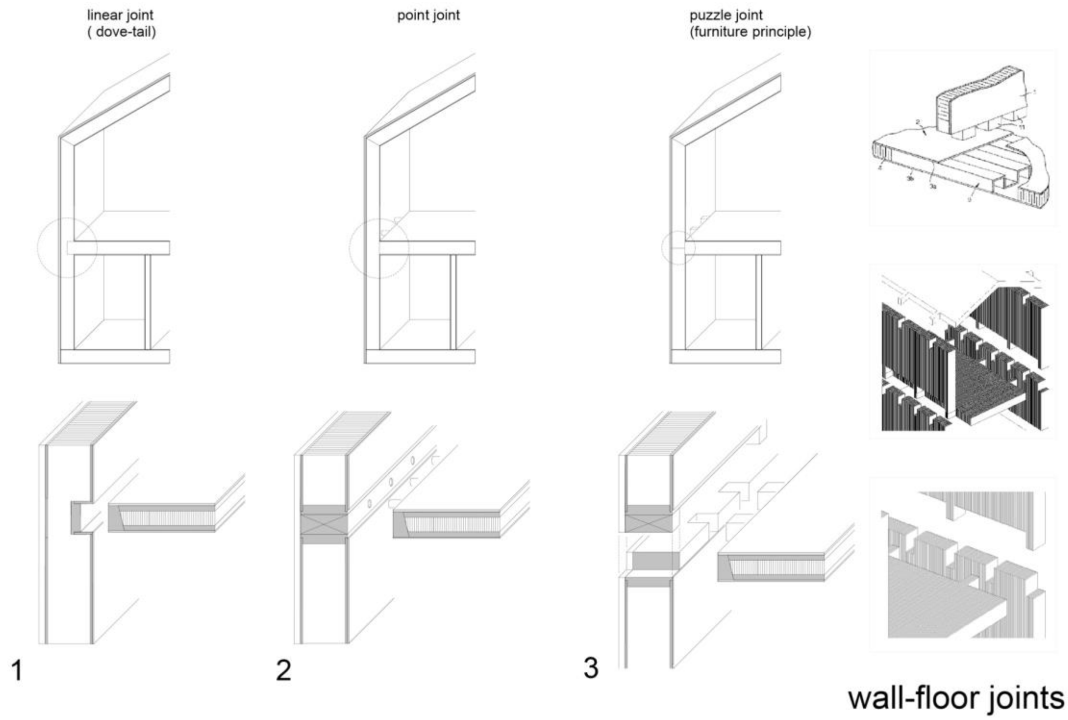


Figure 7. Özlem Ayan's wall-floor cardboard panels joints for a two-story building. Source: Özlem Ayan

main thermal and acoustic components of the building. Mechanical tests performed on the Wikkelhouse's structure evidenced the incidence of using cardboard sheets made from virgin fibers and correct execution of the adhesive's drying process into the overall strength of the structure (Van der Meer 2013; Latka 2017, 238). The interior facing, a 10 mm thick plywood board, works as a vapor barrier. On the exterior, the laminated cardboard plates have protection consisting of a water-resistant but breathable textile, and a ventilated façade system made of vertical treated-wooden laths and a treated-wood siding as exterior finishing.

The *Open Source: Cardboard Pavilion* (Schütz 2018), on the other hand, utilizes a combined cardboard-frame/cardboard-plate system. Figure 10 offers an overview of the Cardboard Pavilion's different components. Schütz implemented this experimental system to construct a semi-permanent container-like building of 5 m length, 3.3 m width, and a 3.6 m height. The building used honeycomb boards mostly in combination with plywood components for the reinforcement of the joins. Six quadrangular frames made of folded planks of honeycomb boards make the building structure to which the cardboard plate system is attached following the next order. From the inside to the outside, the first layer consists of 60 mm thick honeycomb boards attached to the structural frame using a conventional adhesive. Next, a ventilated façade system comprises two elements: wooden laths glued to the first layer to create a ventilation gap and 30 mm thick honeycomb boards as exterior siding. This configuration applies to the façades and the roof. However, the floor has a variation where the external 30 mm honeycomb board layer was replaced with a plywood board. Schütz opted for applying a sealing tape in the panel joins and layers of plaster on the whole surface of walls and roof to protect the envelope from the natural elements. The plaster, a powdery mineral mixed with a binder in a ratio of 1:1 and applied manually using a spatula, helps to protect the structure from UV rays and temperature fluctuations. The façade coating is applied only on the top layer of the boards. The method makes the board easy to recycle since no fasteners are used and, therefore, they are easy to remove and although they must be disposed separately. Subsequent monitoring of the experimental structure evidenced cracks in the plaster, raising concerns about its effectiveness. Although this issue might compromise the building's durability, the low-cost plastering

Figure 8. Wikkelhouse fabrication process. Source: Fiction Factory

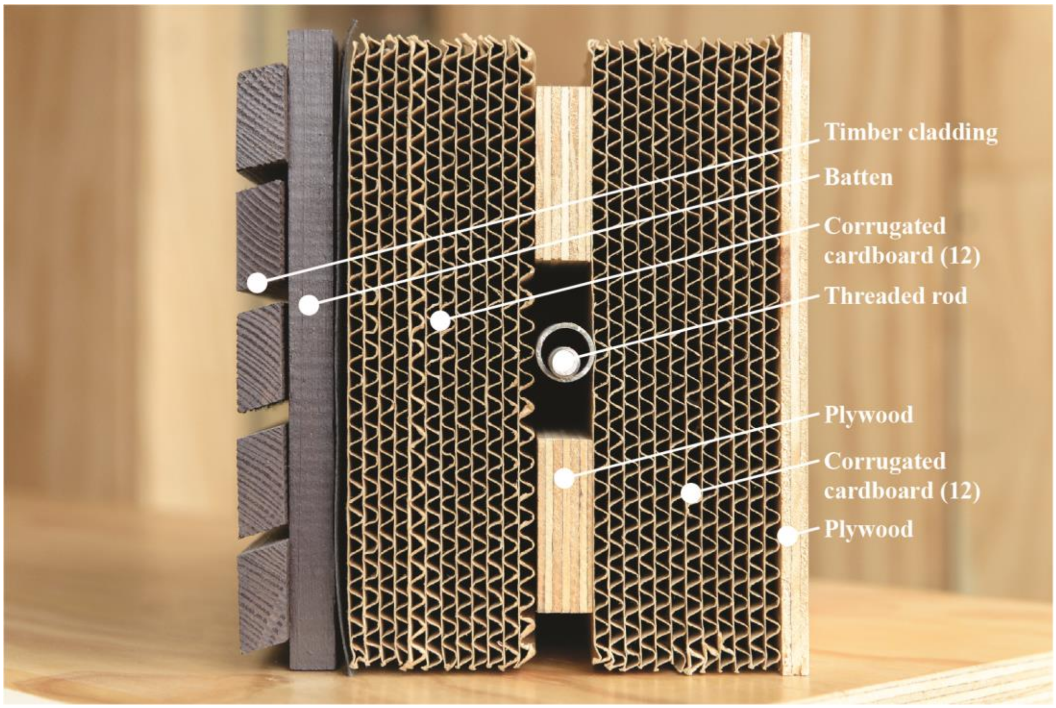


Figure 9. Wikkelhouse's wall detail. Source: Fiction Factory

Figure 10. Cardboard Pavilion's structural components and built prototype's views. Source: Stephan Schütz

method and the easiness of its application are essential advantages compared to a wooden or aluminum exterior siding, especially temporary uses.

4.4.2 Active Vector Structures – Rod or Frame Systems

Paper tubes are the most common cardboard material used in *rod* or *frame structural systems*. The survey determined three main applications of paper tubes in these systems: a) 73% columns; b) 42.3% truss or beam; and c) 30.7% frame. Seminal references about the mechanical properties of paper tubes in some buildings designed by SBA between 1991 and 1999 accentuated that relative humidity has a much stronger influence on the dimensional change in length of the paper elements than changes due to creep (McQuaid 2003; Correa 2004). This issue was continually stressed in later works such as The Cardboard Dome in The Netherlands in 2003-4 (Eekhout 2018b).

Another critical characteristic of the paper tube learned is that parallel-wound tubes' compressive strength is 10% greater than spirally wound tubes. Tests performed by SBA reported compressive strength for the first was 113.9 kgf/cm² (1,620.03 psi) and 103.2 kgf/cm² (1,467.84 psi) for the second. By way of comparison, the compressive strength parallel to the Eastern White Pine grain — a typical kind of wood used for construction lumber — is 171.31 kgf/cm2 (2,436.63 psi). This value is 33% greater than spirally winded paper tubes (Green Winandy and Kretschmann 1999). The seams on the tubes fabricated using spiral winding machines weaknesses the component. Nevertheless, spirally winded paper tubes are preferred because they have no limit of length. Other factors that affect the paper tubes' strength are the type of paper used (using virgin fibers instead of recycled increments resistance), winding angle, and overlapping factor of the paper strips used to produce the tubes.

Figure 11 illustrates four practical applications of paper tubes in rod or frame building systems by SBA. The diagrams represent the whole or part of the buildings simultaneously and communicate SBA's structural design advancements using paper tubes. In the first example, Library for a Poet, short segments of spirally winded paper tubes of length 500 mm, and diameter 100 mm form the structure. The tubes connect using wood joints, metal fasteners, and steel rods inside and outside the tubes to consolidate the frame structure. However, the paper elements' low compressive strength showed enough for a structure that supports only the weight of a light metal roofing system. The lateral bookshelves/walls (not included in the diagram) absorbed the more demanding horizontal forces.

In the next example, *Paper House*, the tubes absorbed both the roof weight and horizontal forces. Consequently, the solution used parallel winded tubes of greater size and compressive strength. The tubes connect to the flooring and roofing structure using wood joints and metal fasteners. Up to here, we can see how design and engineering sought to weigh the configuration of tubes, mechanical capabilities, and program requirements to design the structure. In the *Library of a Poet*, the contribution falls on structural principles and less on interior space design, while

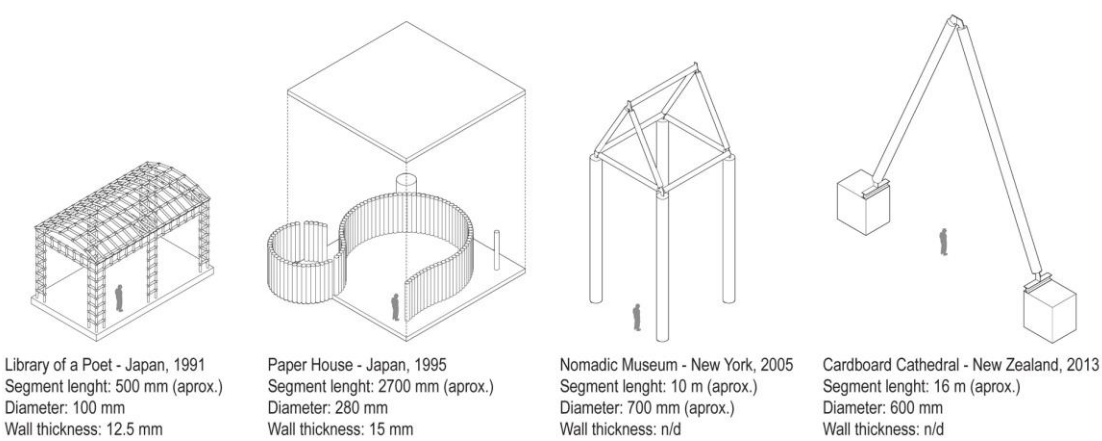


Figure 11. Paper tube structures in Shigeru Ban's works. Source: Authors

Paper House touches both architecture and structure aspects.

The *Nomadic Museum*, built with large-scale spirally winded paper tubes, proposed a different challenge. The building's temporary and "nomadic" conditions required a design based on efficiency, ease of construction, disassembly, and reusability of the parts. The building was dismantled, transported, and then reassembled elsewhere, so more durable steel joins and fasteners instead of wood joins were preferred. The Cardboard Cathedral in New Zealand, on the other hand, is a semi-permanent building (intended life span ten years) and one of the most significant paper tube structures designed by SBA. Each one of the 16 m straight rod components of the roof was made of three segments of paper tubes of 600 mm diameter. These segments cover a wood beam of 16 m inserted in the paper tubes that are the actual load-bearing structure. The wood beams connect at the ends using complex steel joins, criteria adopted for safety and durability regarding other potential earthquakes. It was not possible to determine if the tubes work as structural elements or not. Nevertheless, the building highlights the color, texture, and form of the tubes to create a luminous interior space.

In summary, the main challenges faced by designers when using paper tubes for rod/frame structural systems in these examples were: determining the proper dimensions of paper components (diameter and wall thickness, mainly); learning the compression and bending stress limitations of the tubes; and a proper configuration of joins and fasteners (the examples show that temporary buildings use wood joins and semi-permanent, and permanent structures use steel joins). In the four cases discussed, paper manufacturers produced and supplied material according to designers' structural requirements. This collaboration with manufacturers has been critical for the projects' success, considering there are no guidelines or codes for designing and building with these materials yet.

4.4.3 Active Vector Structures – Dome or Shell Systems

Dome or shell structures were implemented in 36.8 % of all cardboard buildings included in the survey, from which two-thirds correspond to shell structures and one-third to dome structures. The most preferred elements for shell structures are paper tubes and corrugated cardboard/paperboard plates. Dome structures, on the other hand, were built using corrugated cardboard and paperboard plates (85.72%), and only a small part used paper tubes (14.28%). The following paragraphs highlight the fundaments of representative cases found in the survey and research publications.

Buckminster Fuller took advantage of corrugated cardboard plates for his geodesic dome-house projects in the 1950s and 1960s. In the "Environmental Control Device Project" (Stern and Stamp 2016), one of the earliest examples, Fuller and a team of students from Yale University designed and built a full-scale prototype for an geodesic dome shelter. The project consisted of a six-frequency geodesic dome of about 65 m² using corrugated cardboard, adhesives, self-sealing tape, and plastic film for a weather barrier. According to Buckminster Fuller (1953), the dome-house was designed to be acquired in a package of 276 cardboard sheets ready to be transported in a small truck or a car, then folded in triangular trussed modules, and finally assembled by only two people in less than twenty-four hours.

The six-frequency geodesic dome required a strictly modulated construction formed by five types of triangles that could be mass-produced and easily assembled. The triangular modules would be die-cut and waterproofed in a factory and feasible to be assembled by non-skilled people. The on-site assembly would utilize two adhesives: a resin-based adhesive applied in each triangular module's flanges and an adhesive tape along the joints. The design included a mechanical core to allow the house to be self-sufficient and not depend on utility lines. Fuller continued his research of cardboard domes with cardboard plates, and later in 1957, a similar six-frequency icosahedron dome prototype was built at McGill University in Montreal. At McGill, the diamond-shaped modules made of paperboard were covered on the exterior face with an aluminum skin. This series of projects led to Buckminster Fuller's patent for Laminar Geodesic Domes build with corrugated cardboard and were published in (1965), and Figure 12 shows a simplified version of the dome detailing two types of cardboard modules.

Another more recent example of a ten-frequency icosahedron dome but fabricated with paper tubes instead of cardboard plates is the *Paperdome* in the Netherlands in 2003 (Latka 2017, 204; Eekhout 2018b; Ban 2017, 114). The Paperdome design and construction team was formed by SBA, STUT Architects, and Octatube Engineers (main contractor). One of the essential qualities of this example is that it was designed to be dismantled and reassembled, and it had a total lifespan of nine years. Consequently, the designers focused on securing enough material strength to overcome high humidity levels and adequate durability of the paper tubes and steel joints for its reusability. The design demanded extensive research, including mechanical tests of paper tubes, joints, and waterproofing strategies. The model's critical aspects were an adequate number of modules needed, determining the paper tubes segment length (they used several segment lengths between 1200 mm to 1500mm), and achieving an exciting dome-shape. The geometry transitioned from a 16-frequency to an 8-frequency, and finally to a 10-frequency icosahedron dome.

The research on mechanical properties involved close collaboration with a paper tube manufacturer — the paper tube used was made of 100% virgin fibers to assure maximum strength. Previous SBA's works demonstrated that making holes in paper tubes for passing through bolts or screws to connect with joins decreased the durability and strength of the paper tube components. Hence, this project implemented an innovative joint method that allowed pre-stressing the paper tubes with steel joints at the end of the tubes without using bolts or screws to connect them. This solution, proposed by Octatube Engineers, was a significant innovation reapplied in later SBA and Octatube Engineers paper tube structures. To protect the tubes from humidity, they covered the tubes with a varnish applied in the whole exterior surface and partially applied in the interior surface. Finally, they covered the dome with a light waterproofed membrane. Figure 13 illustrates the final placing process of the dome and a detail of the structure.

Regarding shell structures, what made possible the construction of the *Japan Pavilion* in Hannover in 2000 was the very high bending strength of paper tubes: 1.42 to 1.52 times greater in comparison to their compressive strength (McQuaid 2003). The double-curved grid shell was built using paper tubes up to 40 m in length. Even though the architect claimed the structure could resist the structural loads using paper tubes only, German safety standards imposed the use of a complimentary wooden lattice structure. Furthermore, in a later example of paper tube structure, Preston and Bank (2012) designed and built a "temporary outdoor sculpture" by placing several spirally winded paper tube arches along a water canal. Figure

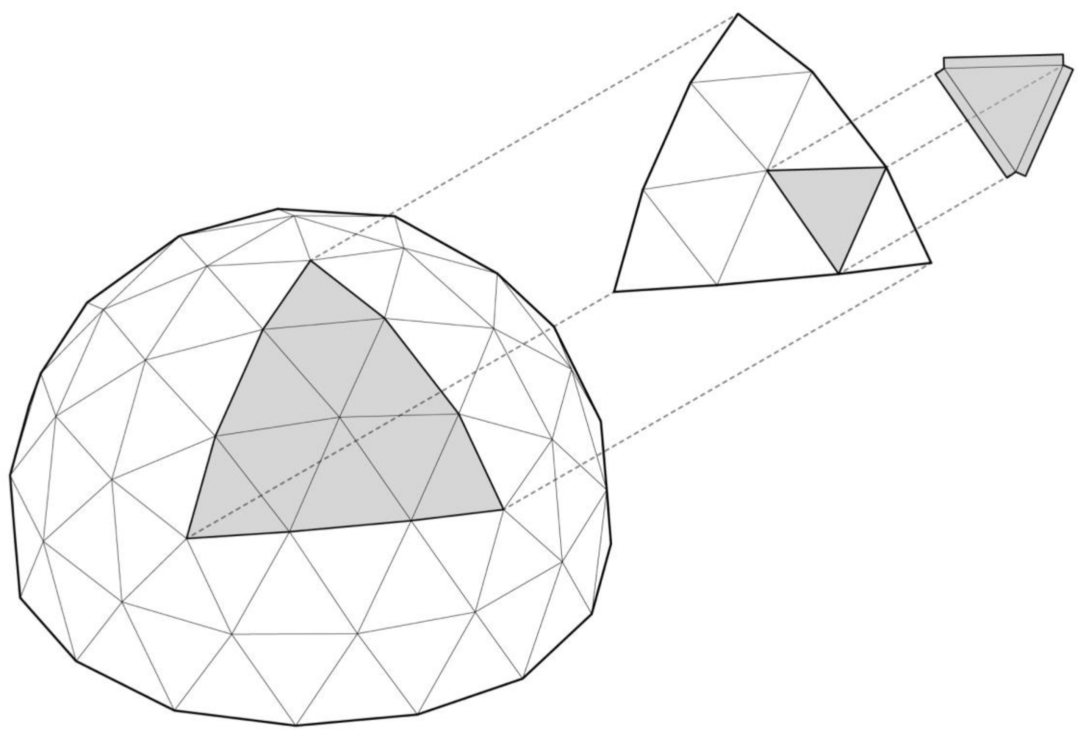


Figure 12. Example of a geodesic dome with cardboard module's detail. Source: Authors

14 shows two views of the paper tubes sculpture with an appreciation of the different arches and paper tube joints. Preston and Bank studied the maximum bending stress values of paper tubes of different diameters and used the results to determine the arches' final design. Their experience highlights the importance of combining engineering analysis and architectural design, mainly to increase safety when using these types of paper components to construct domes, shells, or arches. Their work also set a methodology for calculating and designing paper tube arches. Similarly, an exploratory study led by Shah (2017) tested the construction of a double-curved shell made of paper tube arches. It analyzed the temporary building's structural performance to learn

Figure 13. Paperdome’s assembly process and interior view detail showing steel joints. Source: Octatube Engineers

more about this exceptional but unknown material for shell structures.

5. Conclusions

The study identified three areas of inquiry that are critical to advance the use of cardboard in architecture. The first is *cardboard material properties* with a special focus on topics such as strength, durability, water proofing, and fire proofing. Existing studies implemented internal and external strategies that included combination of cardboard with other more resistant facing materials during construction (e.g., aluminum or wood facing, hybrid construction with wood), cardboard material reinforcement by adding water/fireproofing chemical components during production in the paper mill, and reinforcement by design through shape adjustments of building elements made of cardboard to increase strength. Future works in this topic points towards making cardboard materials more resistant from the paper production itself

Figure 14. Portals to an Architecture exhibition views at University of Wisconsin-Madison. Source: Steve Preston and Lawrence C. Bank

by adding eco-friendly components to keep cardboard recyclable.

The second area of study is about *exploring different applications of cardboard products in buildings*. This area helps to understand the convenient ways of using cardboard products to build components concerning shape and properties. The major contributor to this area of inquiry are universities through research labs and courses where students in the design fields speculate and build prototypical applications of cardboard products for buildings. The experimental and educational nature of these works give designers the freedom to create and build hypothetical applications. Most of these experiences are for temporary uses; however, they create a material and visual archive of tentative cardboard architecture that is very useful as a reference for future applications. Future work in this area could focus on documenting these material experiences to inform and inspire designers and builders.

The third area is about *structural design*. Research found in this area investigates the role of cardboard components in a building and offer basic concepts for designers to consider. Though, there is still much work to be done to systematize cardboard structural criteria to make it easier for designers to use cardboard products as structural elements. This study identified two main structural categories implemented in research and practice so far: a) Buildings that use active surface structures with flat or folded elements made with panels or plates; and b) Buildings that use active vector structures commonly made with linear elements (rods) to build framing systems, domes, and shells. These two categories have been implemented to build small- and large-scale cardboard buildings with different usage time from temporary to permanent.

This study summarizes the fundamentals of cardboard architectural design and a set of strategies proposed by different authors to decrease cardboard strength degradation due to creep, humidity, and fire. These are, according to the publications reviewed, the major weaknesses of the material. Some of the works discussed offer feasible and environmentally friendly strategies to protect cardboard from humidity and fire, adding additives during the fabrication process or through impregnation processes. The procedure to reduce creep varies from using high-quality cardboard products fabricated with virgin fibers instead of recycled fibers to strengthening cardboard structures by combining them with other more conventional building materials such as steel, timber, fabric, and others.

Although this study is limited to mostly formal research publications, formal architectural practice, and cardboard architecture in developed countries, the results offer many critical insights into the use of brand-new cardboard products provided by paper factories for architecture. Besides continuing working on strength improvement, waterproofing, and fireproofing strategies, further research could also revive early initiatives to make cardboard construction more accessible, exploring practical fabrication strategies of cardboard products. This approach could extend the use of cardboard products to self-build architectures. This research area could include the use of low-tech and digital fabrication strategies adaptable to local cardboard production in recycling centers in both developed and developing countries.

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