Comparative Analysis of Paper-based Building Envelopes for Semi-permanent Architecture

Original Proposals and Suggestions for Designers

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Abstract

The presented article is a review of building envelope designs where paper-based products are used as the main material. Paper-based products, especially honeycomb panels and corrugated cardboard provide good thermal insulation properties, affordable prices, and relatively low environmental impact. Paper as a building material has been occasionally used in building envelopes in the past several decades, however, no extensive research has been made on this topic. This study aims to organise knowledge about the design of paper envelopes and help designers in making deliberate and environmentally responsive decisions. Seven different envelope designs were described, evaluated, and compared to each other, three of which were designed by the authors of this article. Particular attention was given to their structure, selection of materials, method of protection against external conditions, thermal insulation properties, and resistance to destructive factors. Based on this analysis, tendencies in designing envelopes made of paper-based materials were described and guidelines for designers were formulated. According to the analysed case studies, the most important factors in semi-permanent paper-based envelope design were indicated. These factors include the core with high thermal resistance, durable protective layer combined with additional impregnation or membrane, and paper core ventilation system.

Keywords

building envelope, paper in architecture, semi-permanent architecture

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1 INTRODUCTION

A building envelope is a system of building components that separates the indoor and outdoor environment and protects the indoor climate of a building from external conditions. Ensuring thermal, acoustic, and visual comfort, tailored to the specific type of building, climate, and the needs of its users, is the key function of the envelope (Oral et al., 2004). Walls are, by virtue of their size, the fundamental part of the envelope, and are usually clad in concrete (Nowak & Brzezicki, 2020), timber (Sandak et al., 2019) or even fragile glass (Brzezicki, 2014). Walls - understood as the vertical part of an envelope - usually comprise the largest area in comparison to its other elements and prevent the significant part of the heat loss or gain (Sadineni et al., 2011). Moreover, external walls are often one of the most material-consuming parts of the building structure, thus their design is of vital importance in the overall environmental impact of the building.

1.1 PAPER PRODUCTS AND PROPERTIES

Paper is widely regarded as a material of low mechanical strength and low resistance to damage. It is combustible and extremely fragile when in contact with water, as every 1% increase in the material's moisture content results in approximately a 10% loss in its mechanical strength (Eekhout, 2008). While a single sheet of paper can not be considered a building material, commonly used paper-based products have much better characteristics, owing to their specific structure. The most popular products that can be applied in building envelope design are described below.

- Corrugated cardboard (CC) – a material composed of alternating flat and corrugated sheets of paper. The most popular flute sizes for building applications are A-flute (approx. 5 mm high), B-flute (3 mm), and C-flute (4 mm). A single sheet of corrugated cardboard usually consists of 2-5 layers of paper, with both surfaces flat, or one flat and one corrugated. Depending on the flute orientation, layers made of this material may have good thermal properties (in the axis perpendicular to the direction of the flute) or mechanical strength (in the axis parallel to the direction of the flute).

- Paper honeycomb panels (HP) – a three-layer product made of a honeycomb-shaped core laminated between two layers of paper. The commonly used panel thicknesses are 50, 25, and 12.5 mm with a standard cell size of 14 mm. Owing to their characteristic structure, the panels have a high compressive strength perpendicular to the surface, despite their low weight. Moreover, honeycomb panels provide relatively good thermal insulation.

- Paperboard (PB) – the most basic one of the discussed products, a flat, full layer of paper, usually 1-4 mm thick. Most paperboards consist of a filler layer, made of recycled paper, laminated between two top liners. It does not provide insulation, but when applied in a thicker layer it can act as a fire barrier due to its high density.

- Cellulose fibre (CF) – blown-in insulation produced from recycled newspapers, often with an addition of fire retardant. Cellulose provides very good thermal and acoustic insulation as well as low environmental impact, however, being a loose material it requires additional structural elements. This is the only paper-based product widely accepted in the building code.

- Paper tubes, U-shapes, and L-shapes – linear elements produced by laminating several layers of paper in the desired shape. These products, in particular paper tubes, can be used as structural elements.

All above-mentioned materials are mass-produced, affordable, and widely available. Furthermore, paper, as a natural material, has a low environmental impact, can be recycled up to seven times, and does not negatively affect the environment if landfilled (Schonwalder & Rots, 2007). According to Secchi, a 15 mm thick paper honeycomb panel has a lower non-renewable energy demand per kg than any of the conventional insulative materials, i.e., 12% lower than mineral wool and more than six times lower than expanded polystyrene (Secchi et al., 2016). Furthermore, in Čekon's research paper, honeycomb panels were proven to have a lower environmental impact, during the production stage per amount of material needed to achieve the required insulation performance, than mineral wool and PIR panels (Čekon et al., 2017). Additionally, corrugated cardboard presents good environmental properties; in Asdrubali's research, the overall environmental impact of the manufacturing stage for C-flute, recycled fibre corrugated cardboard, was lower than for XPE, EPS and rock wool (Asdrubali et al., 2016). Moreover, in the analysis by Campean, even the virgin fibre corrugated cardboard was proven to consume twice as little energy during production than polystyrene insulation (Câmpean et al., 2020).

1.2 PAPER-BASED BUILDING ENVELOPES

Paper attracts architects' interest thanks to a rare combination of low cost and good environmental properties. Although the most commonly applied products in the construction industry are paper tubes, used as columns or truss elements, paper products are also useful in building envelope design. These materials are usually associated with temporary and emergency architecture – a Japanese architect, Shigeru Ban was a pioneer of implementing paper in contemporary architecture. Ban designed emergency shelters (Paper Log House), temporary social buildings (Paper Nursery School in Yaan), and exhibition structures (Japan Pavilion for 2000 Expo in Hannover) - see Figure 1. However, properly selected and protected paper-based products can also be used in the envelopes of semi-permanent buildings, acting as a main structural and insulative material. Several envelopes have been already designed and some were successfully implemented in completed buildings. These envelopes will be described in detail and compared in the following sections.

FIG. 1 Shigeru Ban's architecture made with paper tubes - Paper Log House (Photograph Copyright by J. Latka, 2013) and Japan Pavilion (Photograph Copyright by M. Brzezicki, 2000)

1.3 THE NOVELTY OF THE PRESENTED APPROACH

Despite the completion of several buildings with paper envelopes, there is still a lack of comprehensive research on this subject. Furthermore, most of the research that has been conducted on paper in architecture pertains to its mechanical strength, which is a secondary criterion for non-structural elements, such as envelopes. For this reason, each new paper envelope project requires a separate study to be conducted by its designers, which significantly lengthens the design process and often negatively affects the quality of the proposals. As a result, many separate studies have been already carried out, focusing mainly on a narrow range of materials and properties directly related to the project. This study aims to gather and organise knowledge about the design of paper envelopes and help designers in making conscious decisions. Uniform criteria were applied to the analysis of all the envelopes discussed, which led to a comparison of different design approaches.

2 RESEARCH OBJECTIVES AND METHODOLOGY

The objectives of the presented research were to investigate the structure and performance of selected paper-based building envelopes. The envelopes were assessed in terms of their structure, diameters, durability, fire safety, and thermal conductivity. Comparison between them allowed different design strategies to be identified and similarities to be pointed out. As a result, several guidelines for designers are formulated at the end of this article.

2.1 CASE STUDIES SELECTION

There is no fixed definition of semi-permanent buildings, however, they are usually defined by reference to temporary and permanent structures. The usability of temporary housing is between six months and several years and the lifespan of a permanent building is assessed between 50 and 120 years (Latka, 2017). Therefore, the semi-permanent building lifespan can be set at more than 5 and less than 50 years. For paper-based building envelopes, the main criterion that distinguishes envelopes for temporary and semi-permanent buildings is the level of protection against the natural condition. Due to the limitations of the material, permanent paper-based buildings have not yet been designed.

Paper-based building envelopes for the analysis were chosen from published projects and completed buildings, based on three criteria:

- the designed envelope consists of at least 70 % paper-based materials (by volume) and cellulose fibre insulation is not the only paper material used;
- the envelopes provide noticeable thermal insulation (with U < 1 W/m^{2}K);
- the building's expected lifespan is 5 years or more.

Seven different envelopes were chosen, including two constructed buildings, two prototypes, and three theoretical, academic designs. The number of available case studies regarding paper-based envelopes with a set lifespan is very limited. The vast majority of paper architecture examples are temporary structures, pavilions, and indoor elements. Although these case studies often present unique technical ideas, they do not provide thermal insulation nor protection against natural conditions, which are crucial for building envelopes.

This article covers all the case studies for which the available data allowed them to be analysed, therefore, the review can be considered comprehensive for the current state of the art.

2.2 AUTHORS' CONTRIBUTION

Three of the presented envelopes (Nos. 5, 6, and 7) were designed with the participation of the authors of this article. Design No. 5, House of Cards, was a result of the workshops organised with the cooperation of the Delft University of Technology, where the prototype of Jerzy Latka's design was built by a group of students. During the next edition of the workshop, the prototype of TECH 04 was prepared according to the project of Jerzy Latka and Agata Jasiolek. The Tube Envelope design was part of the thesis project of Agata Jasiolek, supervised by Marcin Brzezicki.

2.3 ANALYSED FEATURES, CRITERIA OF COMPARISON

The analysis was based on authors' publications and technical drawings of the envelopes and focused on the properties affecting the functional qualities of the designs. The study was conducted in three main areas:

- the envelope assembly and dimensions - type and composition of materials, thickness, weight;
- thermal conductivity;
- durability of the assembly - resistance to water and mechanical damage, fire safety.

2.3.1 Structure and Dimensions

Technical drawings published by the designers were a source for a description of the envelope structure and materials used. When calculating the thickness, dimensions declared by the designers were used, and if necessary, the authors referred to standard thicknesses of specific materials (for example, corrugated cardboard of a particular flute type). In several cases, the values were estimated based on the thickness of individual layers in the analysed drawings.

TABLE 1 Properties of selected paper-based products

MATERIAL	THICKNESS [MM], TYPE	WEIGHT [KG/M^2]	THERMAL CONDUCTIVITY [W/MK]
paper honeycomb panel	50	1.80	0.125
	25	0.90	0.095
corrugated cardboard	A-flute, 2-layer	0.40	0.047
	A-flute, 3-layer	0.55	0.047
	BC-flute, 7-layer	0.70	0.050

The weight per square metre of the envelope was obtained using layer thicknesses and average material density from EN ISO 10456:2007 standard for conventional building materials. The actual weight of paper-based products depends on the weight of individual layers and may vary depending on the manufacturer or application. For this analysis, the averaged values of weight per square metre presented in Table 1 were used. The estimated weight of glue and varnishes layers was also included in the calculation. However, it needs to be stressed that presented weights are estimated and do not include additional point fixing and linear elements, such as joints, battens, frames, and external structural components.

2.3.2 Thermal Conductivity

The thermal conductivity, if not provided by the designers, was obtained by the authors via heat flow simulation in HTflux software, in accordance with the standards EN ISO 10077-2:2007 and EN ISO 10211-2:2012. Due to the insignificant thermal resistance of the finishing layers, only paper-based core layers were analysed. The thermal conductivity of conventional materials used in simulations was based on EN ISO 10456:2007 standard. For corrugated cardboard and honeycomb panels, values based on laboratory tests, presented in Table 1, were applied (Čekon et al., 2017; Heyden & Lange, 2017; Russ et al., 2013; Salavatian et al., 2019). Significant differences in total weights and thicknesses of the envelopes hinder a relevant comparison of their effectiveness in terms of thermal insulation. To obtain comparable data, two ratios were calculated. The total thermal resistance of the partition was divided by its thickness (R:d ratio) and unit weight (R:m ratio).

2.3.3 Resistance to Destructive Factors

The envelope's durability was assessed based on finishing materials used, in three areas: resistance to water, combustibility, and resistance to mechanical damage. The durability of external (outdoor) and internal (indoor) surfaces was rated separately. In each category, a descriptive three-grade scale was used, according to the following criteria.

For combustibility

- non-combustible – non-combustible materials or combustible materials with fire retardant (class A1, A2 or B according to EN 13501-1 standard);
- difficult to ignite – materials with limited combustibility;
- combustible – combustible materials without fire retardant.

For water resistance

- watertight – materials resistant to long-term exposure to water (e.g. roofing materials);
- high resistance – materials resistant to short-term exposure to water;
- medium resistance – materials resistant to short-term exposure to water, prone to damage and leaking.

For resistance to mechanical damage

- high resistance – durable materials used in permanent buildings;
- medium resistance – materials with a limited durability;
- low resistance – polymer films and paint coatings.

The heat of combustion per square metre of the envelope, important in terms of building fire safety, was calculated in accordance with the materials' calorific values provided in EN 1991-1-2:2002 standard. Point and linear elements were excluded from the calculation, as explained in the previous section.

3 CASE STUDIES CHARACTERISTIC

Seven paper-based envelopes are described below in chronological order. Authors focus on the materials used and their configuration, durability, and insulative properties of the presented designs.

3.1 THE ENVELOPE OF WESTBOROUGH PRIMARY SCHOOL

A semi-permanent social building for school children was designed by Cottrell and Vermeulen Architecture and Buro Happold Engineers (see Figure 2). Built in 2001 in Westcliff-on-Sea, United Kingdom, it was the first permanent paper-based structure erected in Europe. Paper elements were used as the main building material to minimise the environmental impact of the building. A paper-based envelope (for both roof and walls) is mounted to the structure of paper tube columns and timber roof truss.

FIG. 2 Westborough Primary School building (From https://www.cv-arch.co.uk/westborough-cardboard-building/)

TABLE 2 Westborough Primary School building and envelope characteristic

WESTBOROUGH PRIMARY SCHOOL			
Type of building		Social building for school children	
Authors		Cottrell and Vermeulen Architecture	
Date and location (if applicable)		2001, Westcliff-on-Sea, United Kingdom	
Lifespan	20 years	Main materials	paper honeycomb, 50 mm thick, 3 layers paperboard, 4 mm thick, 4 layers paperboard precoated with PE film, 1 mm thick, 1 layer
Load-bearing	no		
Stage	built		
Ventilation	yes		
Weight [kg/m^2]	41.62	Internal surface protection technique	cellulose pinboard with fire retardant, 9 mm thick
Thickness [m]	0.23		
U [W/m^{2}K[	0.72	External surface protection technique	breather membrane fibre-cement board, 8 mm thick
Heat of combustion [MJ/m^2]	549.73		

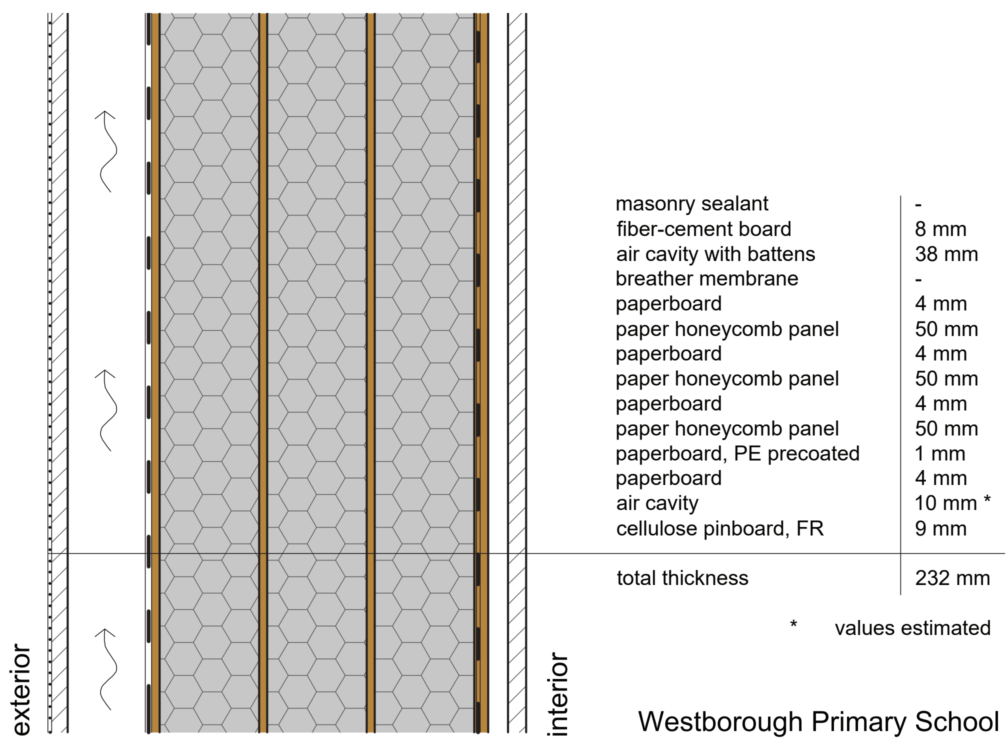


FIG. 3 Westborough Primary School envelope section

The envelope is composed of alternating layers of 50 mm thick paper honeycomb panels and 4 mm thick paperboard laminated together and fitted into timber frames, creating the insulative core with a total thickness of 167 mm. The internal surface of the envelope is covered with a polyethene pre-coated paperboard layer and an non-flammable cellulose pinboard. The external surface is ventilated to prevent water condensation inside the panels and covered with a breather membrane and fibre-cement board (Cripps, 2004; Latka, 2017). Detailed information regarding the envelope is presented in Table 2 and Figure 3.

The building, with a declared lifespan of 20 years, and following minor repairs to the roof, is still in use in 2021. The chosen finishing materials provide very good protection against fire, water, and mechanical damage. It needs to be mentioned that the envelope insulative properties are rather low. As stated by the designers, it was not laboratory tested and U-value calculations were performed based on corrugated cardboard thermal conductivity (Cripps, 2001). However, as proven by other research, the insulative properties of honeycomb panels are significantly lower than for corrugated cardboard; the thermal conductivity of a 50 mm thick panel was measured as 0.125 W/mK (Salavatian et al., 2019). Despite moderate thermal resistance, the envelope is relatively thick (231 mm) and heavy (41.62 kg/m^2) due to several layers of paperboard used.

3.2 THE ENVELOPE OF CARDBOARD DWELLING IN BRAZIL

A semi-permanent, cardboard-based residential building was designed in 2003 by Mirian Vaccari. The architect aimed to design housing for the reurbanisation of shanty towns in São Paulo, Brazil, however, they have never been constructed. Cardboard was chosen as an affordable and available material. The building structure is based on paper tubes and steel cable truss with cardboard-based envelope panels.

The envelope consists of two panels with an unventilated air cavity between them. Each panel is composed of a 25 mm thick paper honeycomb laminated with a 5 mm thick, A-flute corrugated cardboard layer on both sides. The external surface of the wall is protected with recycled drink cartons cladding (Tetra Pak - paper laminated with aluminium and polyethene film), and both internal and external surfaces are finished with an unspecified paint (Vaccari, 2008). Detailed information regarding the envelope is presented in Table 3 and Figure 4.

TABLE 3 Cardboard Dwelling building and envelope characteristic.

CARDBOARD DWELLING IN BRAZIL			
Type of building		Residential building	
Author		Mirian Vaccari	
Date and location (if applicable)		2003, São Paulo, Brazil	
Lifespan	semi-permanent, (unspec.)	Main materials	paper honeycomb, 25 mm thick, 2 layers corrugated cardboard, 3-layer, A-flute, 4 layers unventilated air layer
Load-bearing	no		
Stage	unbuilt		
Ventilation	no		
Weight [kg/m^2]	6.18	Internal surface protection technique	paint (unspecified)
Thickness [m]	0.10		
U [W/m^{2}K]	0.84	External surface protection technique	recycled drink cartons, paint (unspecified)
Heat of combustion [MJ/m^2]	161.38		

Vaccari provides two unique design solutions: using recycled drink cartons and an unventilated air cavity. Reused Tetra Packs are watertight and beneficial from an environmental perspective, although the designer does not specify their assembly method, which might be difficult to implement in larger-scale production. Moreover, the inside surface of the panel has no protection against mechanical damage and both surfaces are flammable , which negatively affects the safety of the structure. The wall core has low insulative properties, but the air cavity is exceptionally light (6.18 kg.m^2), which also translates into low heat of combustion (161.38 MJ/m^2).

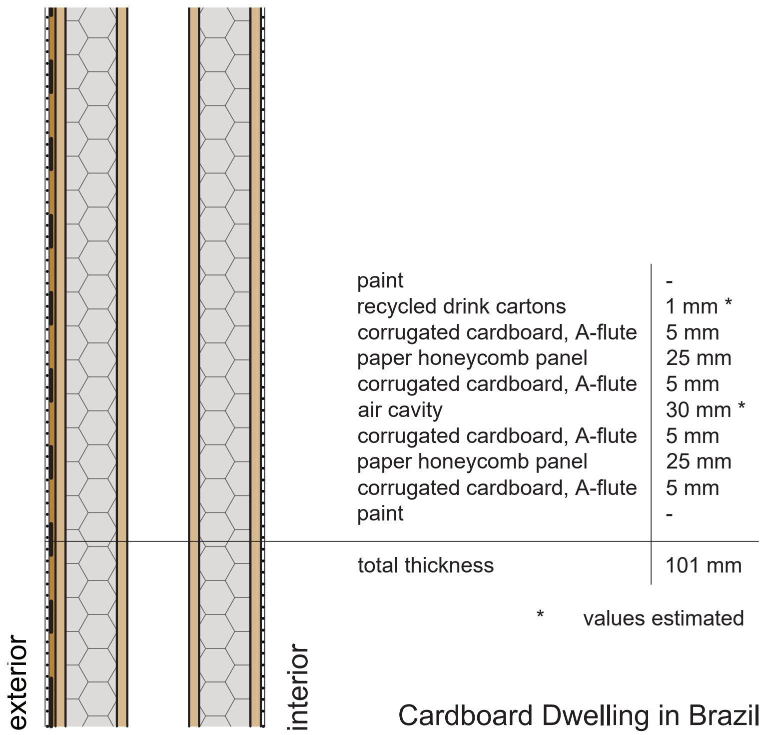


FIG. 4 Cardboard Dwelling envelope section

3.3 CATSE WALLS

A series of paper-based walls for various applications was designed by Ozlem Ayan in 2009, based on findings of CATSE (Cardboard in Architectural Technology and Structural Engineering) research team from ETH Zurich. All of the walls, including the exterior, interior, structural, and insulative ones, were incorporated in a conceptual residential project, to present the suggested application. The structural, insulative external wall, type No. 4, was chosen for this article analysis, as the most relevant example.

The unique element that connects all the Ayan's designs is a corrugated honeycomb core. The core is produced by laminating several layers of corrugated cardboard and cutting the obtained block into slices. The way the slices are arranged in the created core determines its insulative and mechanical properties. The discussed wall is composed of a 450 mm thick corrugated honeycomb core. Its internal surface is covered with steel facing or with plywood. The external surface is ventilated and covered with steel facing and steel cladding or vapour barrier and wood cladding (the steel-finished variant was used in this comparison) (Ayan, 2009). Detailed information regarding the envelope is presented in Table 4 and Figure 5.

TABLE 4 CATSE building and wall characteristic

CATSE WALL NO 4			
Type of building		Residential building	
Author		Ozlem Ayan	
Date and location (if applicable)		2009, no location	
Lifespan	10 years	Main materials	Corrugated cardboard honeycomb panel
Load-bearing	yes		
Stage	unbuilt		
Ventilation	yes		
Weight [kg/m^2]	78.74	Internal surface protection technique	plywood or steel sheet
Thickness [m]	0.51		
U [W/m^2K]	0.12	External surface protection technique	steel facing with steel cladding or vapour barrier with wood cladding
Heat of combustion [MJ/m^2]	960.60		

According to the designer, the wall has very high insulative properties (U = 0.12 W/m^2K), suitable for use even in passive buildings. Excellent thermal properties are reflected in the wall thickness (510 mm) and weight (78.74 kg/m^2). Steel finishing provides high resistance to water, fire, and mechanical damage.

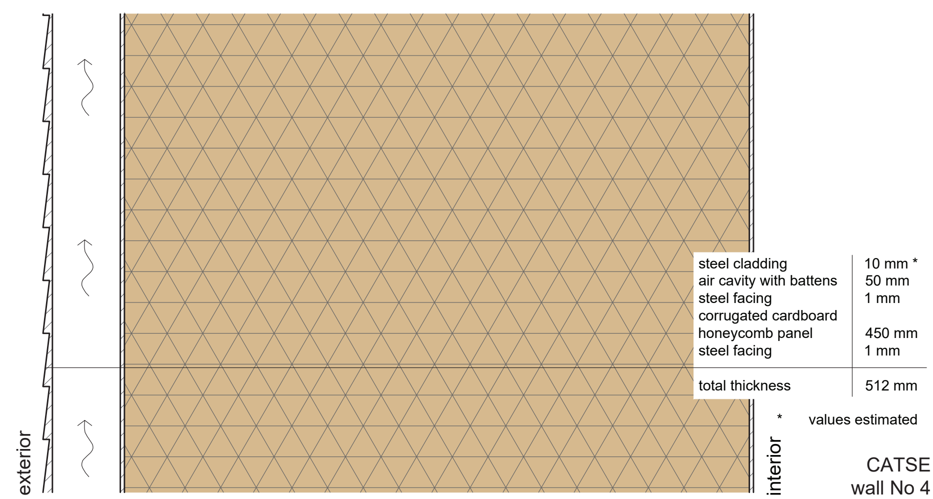


FIG. 5 CATSE wall section

3.4 ENVELOPE OF WIKKELHOUSE

A prefabricated holiday house, designed by Rene Snel in 1996 and developed by Fiction Factory in 2012 in the Netherlands, is the only commercial building in this analysis (see Figure 6). The structure is composed of segments fabricated by wrapping and laminating corrugated cardboard around the house-shaped mould. In consequence, the whole envelope (walls, floor, and roof) are composed of identical layers of materials. The segments, connected by steel rods placed in the cavities between the cardboard layers, provide both structure and insulation.

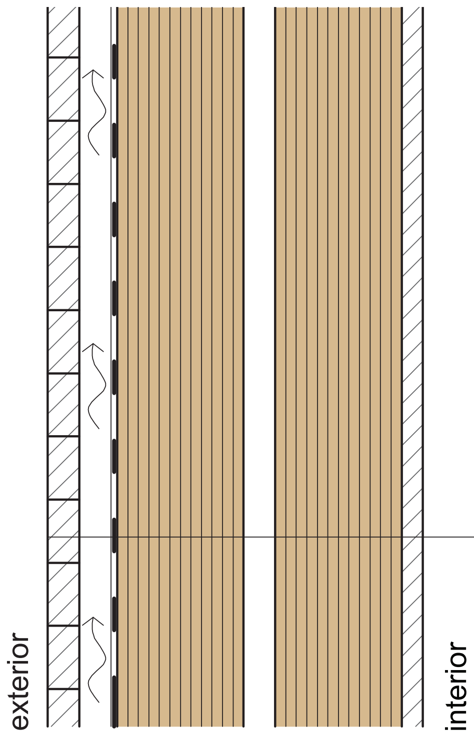
FIG. 6 Wikkelhouse by Fiction Factory. Note. Adapted from the manufacturers website (https://www.fictionfactory.nl/en/wikkelhouse/). Copyright 2020 by Y. Witte

The envelope core is made of 24 layers of 2-layer A-flute corrugated cardboard, with a gap for joining and bracing elements in the middle. The prototype from 2012 was covered with a breather membrane and aluminium sheet on the outside and a kraftliner paperboard on the inside. However, the final product is finished with a breather membrane and wood cladding on the external surface and plywood on the internal surface. It can be assumed that wood is impregnated, though there is no information regarding the products used. Both variants of the envelope are ventilated, to avoid water condensation (Meer, 2013). Detailed information regarding the envelope is presented in Table 5 and Figure 7.

TABLE 5 Wikkelhouse building and envelope characteristic.

WIKKELHOUSE			
Type of building		Holiday house	
Author		Rene Snel (inventor), developed by Fiction Factory	
Date and location (if applicable)		invented in 1996, developed and produced in 2012 in the Netherlands, no fixed location	
Lifespan	50 years (15 years warranty)	Main materials	Corrugated cardboard, 2-layer, A-flute, 24 layers
Load-bearing	yes		
Stage	built		
Ventilation	yes		
Weight [kg/m^2]	27.84	Internal surface protection technique	plywood
Thickness [m]	0.18		
U [W/m^{2}K]	0.35	External surface protection technique	breather membrane wood cladding (aluminium sheet in the prototype)
Heat of combustion [MJ/m^2]	518.85		

According to the official Wikkelhouse website, over eighty houses have been sold by the end of 2020. The envelope provides good insulative properties (U = 0.35 W/m^{2}K) with moderate weight (27.84 kg/m^2). The original wrapped manufacturing method results in minimising the number of joints and potential thermal bridges. Used finishing materials provide sufficient resistance to water and mechanical damage, however, there is no data regarding fire protection.



wood cladding	15 mm *
air cavity with battens	15 mm *
breather membrane	-
corrugated cardboard, A-flute	12 x 5 mm
air cavity, joining elements	15 mm *
corrugated cardboard, A-flute	12 x 5 mm
plywood	10 mm *
total thickness	175 mm

* values estimated

FIG. 7 Wikkelhouse envelope section

3.5 THE ENVELOPE OF HOUSE OF CARDS

The temporary house or emergency shelter was designed by Jerzy Latka and its prototype was built in 2016 in Wroclaw, Poland (see Figure 8). The constructed unit is part of a temporary housing project for refugees and homeless people. The whole design is paper-based, with paper wall and roof panels and structural frames composed of paper L-shaped elements.

The building envelope consists of three layers of 50 mm thick honeycomb panels laminated together in the frame made of paper L-shapes. External honeycomb panels were pre-coated with polyethene film on one side during production. Both surfaces of the envelope are finished with self-adhesive polyvinyl chloride foil. It was suggested by the designer that air cavities in the honeycomb panels could be filled with cellulose fibre to increase insulative properties. Detailed information regarding the envelope is presented in Table 6 and Figure 9.

FIG. 8 House of Cards prototype

The envelope structure is very simple, which makes it easy to produce and recycle. The panels are exceptionally lightweight (5.83kg/m^2), which implies low heat of combustion (122.95 MJ/m^2). On the other hand, this lightweight structure does not provide sufficient thermal insulation, with U = 0.75W/m^2K. Although the foil-based finishing layer provides moderate protection against water, the surface remains flammable and prone to mechanical damage.

TABLE 6 House of Cards building and envelope characteristic

HOUSE OF CARDS			
Type of building		Emergency housing	
Author		Jerzy Latka	
Date and location (if applicable)		2016, Wroclaw, Poland	
Lifespan	5 years	Main materials	paper honeycomb, 50 mm thick, 3 layers
Load-bearing	no		
Stage	built		
Ventilation	no		
Weight [kg/m^2]	5.83	Internal surface protection technique	PE film self-adhesive PVC foil
Thickness [m]	0.15		
U [W/m^2K]	0.75	External surface protection technique	PE film self-adhesive PVC foil
Heat of combustion [MJ/m^2]	122.95		

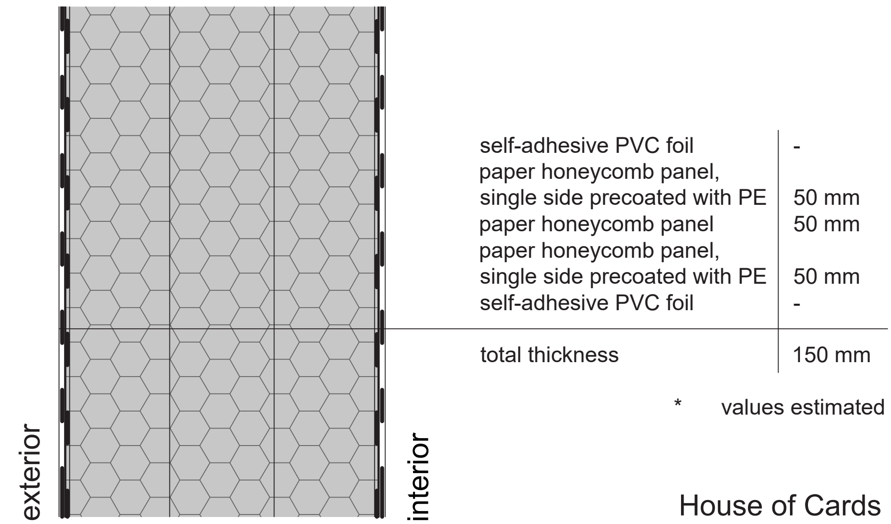


FIG. 9 House of Cards envelope section

3.6 THE ENVELOPE OF TECH 04

Transportable Emergency Cardboard House vol. 4 is an emergency shelter designed by Jerzy Latka and Agata Jasiolek, which prototype was built in 2018 in Wroclaw, Poland (see Figure 10). The facility was designed for refugees and victims of natural disasters. The modular design consists of cardboard-based sandwich panels bent at the construction site to form a one-element roof-wall envelope. The timber structural elements are built in the panels.


FIG. 10 TECH 04 prototype

The envelope modules are composed of a double layer of 25 mm thick honeycomb panels laminated with four layers of 7 mm thick BC-flute corrugated cardboard on both sides. Panels are finished with varnish-coated aluminium sheets from the outside, and polyvinyl chloride self-adhesive foil from the inside. Detailed information regarding the envelope is presented in Table 7 and Figure 11.

The design combines properties of both corrugated cardboard and honeycomb panels, which results in moderate insulative properties (U = 0.55W/m^{2}K) and low weight (9.91kg/m^2). Moreover, the lack of joints between roof and wall panels minimises the risk of thermal bridges, which improves the overall thermal performance of the structure. Aluminium cover, produced to be used as roofing, is watertight, incombustible, and provides high resistance to mechanical damage.

TABLE 7 TECH 04 building and envelope characteristic.

TECH 04			
Type of building		Emergency housing	
Authors		Jerzy Latka, Agata Jasiolek	
Date and location (if applicable)		2018, Wroclaw, Poland	
Lifespan	5 years	Main materials	Corrugated cardboard, 7-layers, BC-flute, 8 layers paper honeycomb, 25 mm thick, 2 layers
Load-bearing	no		
Stage	built		
Ventilation	no		
Weight [kg/m2]	9.91	Internal surface protection technique	self-adhesive PVC foil
Thickness [m]	0.11		
U [W/m2K]	0.55	External surface protection technique	aluminium sheet with protective paint coating, 0,6 mm thick
Heat of combustion [MJ/m^2]	172.35		

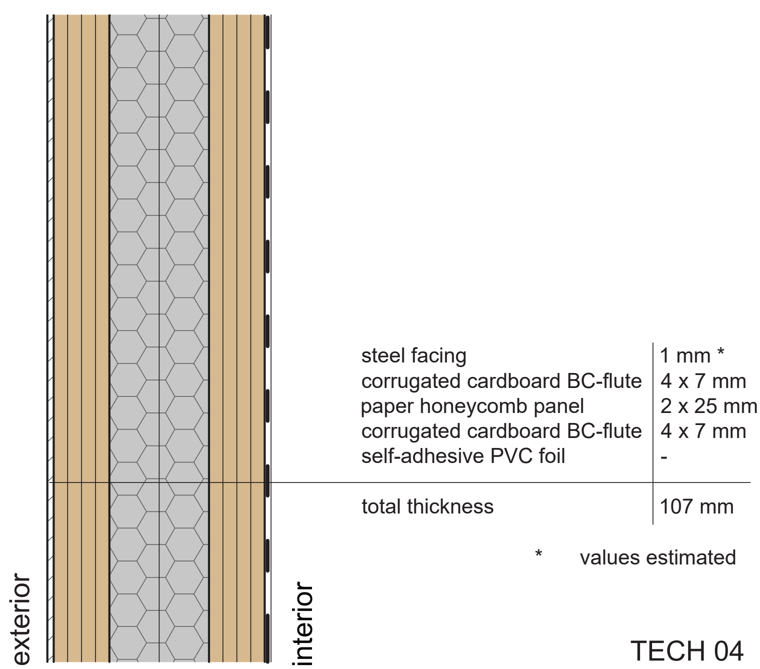


FIG. 11 TECH 04 envelope section Tube Envelope

3.7 TUBE ENVELOPE

The envelope was designed by Agata Jasiolek in 2019 for the glass sorting plant located in Lebork, Poland, as a part of a thesis project supervised by Marcin Brzezicki. The project was not constructed, but the prototype of the single envelope panel was prepared (see Figure 12). The designed production hall with the cross-laminated timber structure is covered with a paper-based envelope both from the side and from the top. The envelope panels are mounted to the grid timber structure.

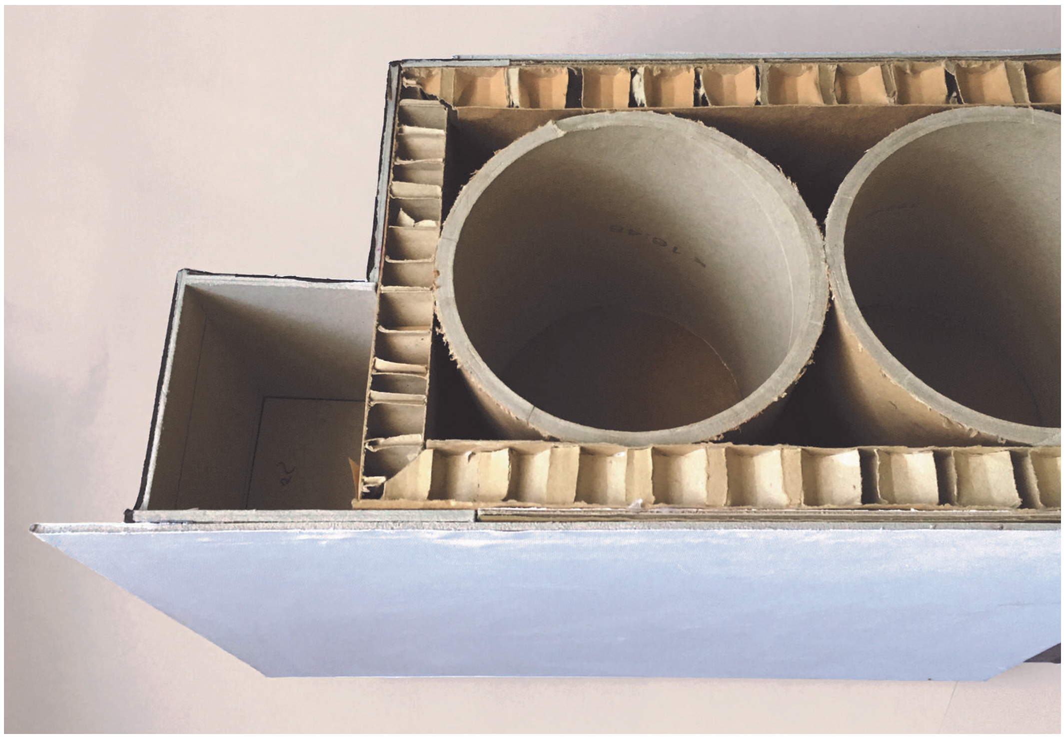


FIG. 12 A prototype of the Tube Envelope panel

The envelope core is composed of paper tubes arranged horizontally, one on top of the other. Each set of paper tubes is enclosed by a honeycomb panel, which forms a closed space around them, a kind of box that is then filled with cellulose fibre. Consequently, paper tubes form an internal structure for blown-in insulation. The core is covered on both sides by a single layer of A-flute corrugated cardboard laminated with recycled polyethene film. Finishing panels consist of 3 mm thick paperboard laminated with watertight, PCV-covered textile, typically used for roofing and tents. Detailed information regarding the envelope is presented in Table 8 and Figure 13.

The Tube Envelope presents a different approach to the paper-based envelope design, incorporating a non-homogeneous layer of cellulose fibre with paper tube structure. Cellulose insulation is made of recycled newspapers, which is beneficial for environmental performance. Fibres provide very good thermal insulation, however, the overall thermal properties of the envelope are affected by uneven heat flow through tube structure - small thermal bridges are formed where the tubes touch each other. The waterproof textile cover provides good protection against water without increasing the weight of the envelope. However, resistance to fire and mechanical damage is moderate.

TABLE 8 Tube Envelope building and envelope characteristic

TUBE ENVELOPE			
Type of building		Industrial building, glass sorting plant	
Author		Agata Jasiolek	
Date and location (if applicable)		2019, Lebork, Poland	
Lifespan	30 years (estimated)	Main materials	paper tubes, 4 mm thick, 177 mm diameter cellulose fibre, approx. 170 mm thick layer paper honeycomb, 25 mm thick, 2 layers
Load-bearing	no		
Stage	unbuilt		
Ventilation	no		
Weight [kg/m²]	29.93	Internal surface protection technique	recycled PE foil PVC-coated membrane
Thickness [m]	0.25		
U [W/m²K]	0.33	External surface protection technique	recycled PE foil PVC-coated membrane
Heat of combustion [MJ/m²]	630.45		

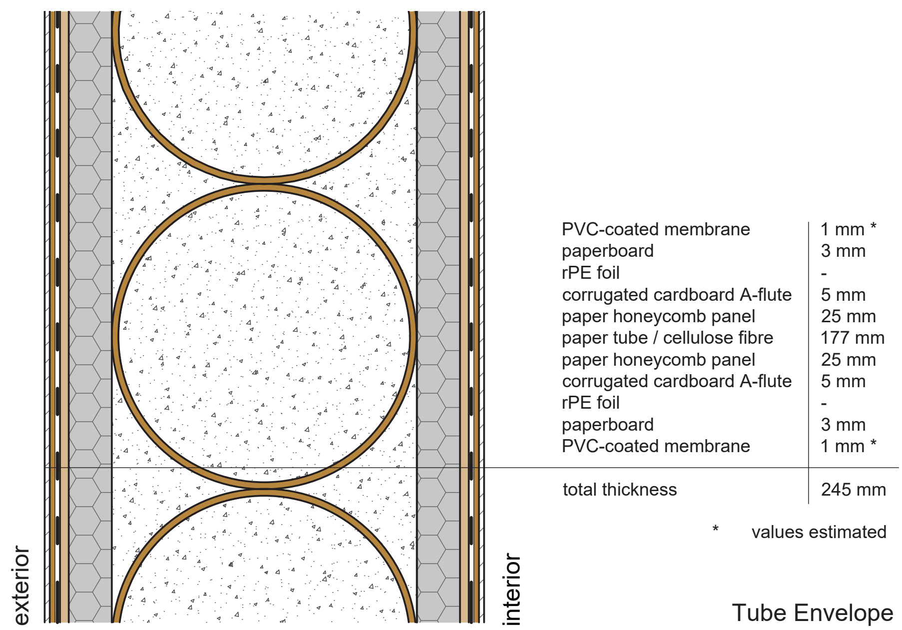
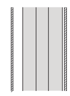
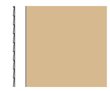
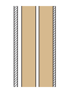
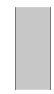
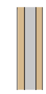
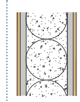


FIG. 13 Tube Envelope section

4 COMPARISON AND DISCUSSION

The envelopes discussed in the previous section present a variety of structures, material compositions, and characteristics. Nevertheless, certain tendencies and correlations among them can be identified. Detailed envelope properties comparison, which will be analysed in this section, can be found in Table 9.

TABLE 9 Characteristics of paper-based envelopes

	WEST-BOROUGH PRIMARY SCHOOL	CARD-BOARD DWELLING IN BRAZIL	CATSE (WALL NO 4)	WIKKEL-HOUSE	HOUSE OF CARDS	TECH 04	TUBE ENVELOPE
cross-section scheme							
lifespan	20 years	semi-permanent (unspec.)	10 years	50 years	5 years	5 years	30 years
load-bearing	no	no	yes	yes	no	no	no
thickness [cm]	23	10	51	18	15	11	25
ventilation	yes	no	yes	yes	no	no	no
weight [kg/ m^2]	41.62	6.18	78.74	27.84	5.83	9.91	29.93
Heat of combustion [MJ/m^2]	549.73	161.38	960.60	518.85	122.95	172.35	630.45
R [m^{2}K/W]	1.39	1.19	8.33	2.86	1.33	1.82	2.70
U [W/m^{2}K]	0.72	0.84	0.12 [1]	0.35	0.75	0.55	0.37
R:d ratio	6.04	11.90	16.33	15.89	8.87	16.55	12.12
R:m ratio	0.033	0.193	0.106	0.103	0.228	0.184	0.101
Insulative core material type	HP	HP, CC	CCH	CC	HP	HP, CC	CF
protection technique – internal surface	FL, AM	VC	AM	AM (+ VC)	2x FL	FL	FL, AM
protection technique – external surface	FL, AM	FL, VC	2x AM	FL, AM (+ VC)	2x FL	AM (+ VC)	FL, AM
combustibility - internal surface	non-combustible	combustible	non-combustible	combustible	combustible	combustible	difficult to ignite
combustibility - external surface	non-combustible	combustible	non-combustible	combustible	combustible	non-combustible	difficult to ignite
Water resistance - internal surface	medium	medium	watertight	medium	medium	medium	watertight
Water resistance - external surface	watertight	high	watertight	high	medium	watertight	watertight
resistance to mechanical damage - internal surface	medium	low	high	high	low	low	medium
resistance to mechanical damage - external surface	high	low	high	high	low	high	medium

[1] value provided by the designer

abbreviations: HP – honeycomb panel, CC – corrugated cardboard, CCH – corrugated cardboard honeycomb panel, CF – cellulose fibre, FL – foil lamination, AM – additional material, VC – varnish coating

4.1 STRUCTURE, MATERIALS USED, AND DIMENSIONS

In the vast majority of cases, envelope panels are sandwich structures created by laminating together several layers of different materials. The only exception to this rule is the Tube Envelope, which core is a nonhomogeneous layer. In all of these designs, the insulative core layer and finishing layers can be distinguished. The core layer, made of paper-based materials (honeycomb panels, corrugated cardboard, cellulose fibre) provides thermal insulation and structural stability, while the external layers protect the core from destructive factors. Non-paper materials, such as foil, metal sheets, wood, and fibre-cement board, are used for finishing layers.

There is a noticeable correlation between envelope thickness, weight, and thermal conductivity. An increase in the insulation properties always implies an increase in weight, while an increase in thickness is more variable, due to the use of different materials. The thickness of discussed envelopes differs from 0.10 m in Cardboard Dwelling and 0.11 m in TECH 04 up to 0.51 m in CATSE. The weights range from 5.83 kg/m^2 in House of Cards and 6.18 kg/m^2 in Cardboard Dwelling, up to 78.74 kg/m^2 in CATSE. Therefore, the heaviest and thickest of the paper-based envelopes (CASTE) is 18% thicker than a standard brick wall and its weight is comparable to the weight of a conventional wood-based wall (see Table 10).

TABLE 10 Comparison of paper-based and selected conventional walls

0	THICKNESS [CM]	WEIGHT [KG/ M^2]	R [M2K/W]	U [W/M2K]	R:D RATIO	R:M RATIO
Westborough Primary School	23	41.62	1.39	0.72	6.04	0.033
Cardboard Dwelling in Brazil	10	6.18	1.19	0.84	11.90	0.193
CATSE (wall No 4)	51	78.74	8.33	0.12 [1]	16.33	0.106
Wikkelhouse	18	27.84	2.86	0.35	15.89	0.103
House of Cards	15	5.83	1.33	0.75	8.87	0.228
TECH 04	11	9.91	1.82	0.55	16.55	0.184
Wood-based wall [2]	28	78.20	5.00	0.20	17.86	0.064
Sandwich panel [3]	18	23.00	5.00	0.20	27.78	0.217
Brick wall [4]	43	263.00	5.26	0.19	12.23	0.020

[1] *value provided by the designer*

[2] *external wall in Steico system – wood-based wall studs, wood fibre insulation, plaster on both sides*

[3] *with mineral wool core - Rukki SPB WEE*

[4] *hollow brick wall with mineral wool insulation and plaster on both sides*

4.2 THERMAL INSULATION

Thermal insulation properties are a key feature of the building envelope, from both the functional and environmental point of view. The analysed envelopes present thermal conductivity from 0.84 W/m^{2}K in Cardboard Dwelling up to 0.37 W/m^{2}K in Tube Envelope, 0.35 W/m^{2}K in Wikkelhouse, and 0.12 W/m^{2}K in CATSE. Thus, CATSE is the only design that is insulative enough to meet the legal requirements of European countries of temperate climate zones, such as Poland. However, in most cases, insulation deficits can be easily fixed by increasing the thickness of the partition. As the presented envelopes vary significantly in weight and thickness, two ratios were used to assess the thermal effectiveness of the designs. The highest thermal resistance in relation to thickness (R:d ratio) can be found in TECH 04, CATSE and Wikkelhouse, and the lowest ones in Westborough PS and House of Cards. The ratio for the former is approx. 10% lower than for a standard wood-based wall and 40% lower than for sandwich panels, but 30% higher than for brick wall. On the other hand, the highest thermal resistance in relation to weight (R:m ratio) was achieved by House of Cards and Cardboard Dwelling, and the lowest one by Westborough PS. The ratio for the former is similar to the ratio of sandwich panels. Moreover, the majority of the analysed paper-based envelopes (excluding Westborough PS) present a higher R:m ratio than the wood-based wall.

4.3 DURABILITY AND RESISTANCE TO DAMAGE

As paper is a fragile material, proper protection against water, fire, microbes, and mechanical damage is crucial for paper-based envelope functionality. Three main protective techniques can be distinguished: application of varnish coatings (VC), lamination with polymer films (FL), or incorporation of finishing layers made of additional materials (AM). Varnishes, films, and foils are affordable and easy to apply, thus they are usually used in temporary structures, however, they do not provide sufficient mechanical damage protection. Non-paper finishing materials, such as metal, plywood, or fibre-cement sheets are significantly more durable and, in some cases, fireproof, but they also increase the weight of the structure. Moreover, the envelope can be also protected by other elements of the structure, preventing the surface of the envelope from direct contact with water, such as a large roof overhang.

In the vast majority of the analysed envelopes, at least two different protection techniques are combined – the most common combination is lamination with additional material layers. In some cases, two layers representing different variants of the same technique were used, for example, lamination with two types of foils. Sometimes the two protective layers are divided by a ventilated air cavity, preventing water condensation inside the partition.

The highest water resistance was achieved in CATSE and Tube Envelope and the lowest in House of Cards. Moreover, Westborough PS and TECH 04 have watertight external surfaces, but weaker protection from the inside. The best surface resistance to fire is provided in Westborough PS and CATSE, as both sides of the envelopes are non-combustible. On the contrary, Cardboard Dwelling, and House of Cards have no fire resistance. CATSE and Wikkelhouse are the most resistant to mechanical damage, good resistance can be also observed in Westborough PS, while Cardboard Dwelling and House of Cards are the most vulnerable to damage. Considering all three destructive factors, CATSE wall can be recognised as the most surface durable design and the House of Cards envelope as the most fragile one.

Heat of combustion of the analysed envelopes is between 122.95 MJ/m^2 for House of Cards and 161.38 MJ/m^2 for Cardboard Dwelling up to 960.60 MJ/m^2 for CATSE; it is correlated with the weight and thickness of the envelope. Furthermore, flammable layers of foils, polymer films, and membranes increase the overall heat of combustion, in contrast to incombustible steel of fibre-cement finishing. It should also be noted that the density of the materials used affects their flammability. Products composed of thin layers of paper, such as corrugated cardboard, are easy to ignite, while dense paperboard layers (used in the Westborough PS) may delay the penetration of fire into the core.

4.4 ENVIRONMENTAL IMPACT

Most designers indicate that low environmental impact was a fundamental reason for investigating paper as a building material for their work. Paper is widely recognised as an eco-friendly material, however, the actual environmental burden of the designed envelopes depends on additional factors, such as the share of recycled fibres in paper production, the type of adhesive, or the possibility to separate and recycle individual row materials. The lack of detailed information restrained the authors from conducting a reliable Life Cycle Assessment analysis; nevertheless, some conclusions could be formulated.

Firstly, the overall environmental performance of the building is strongly connected with the thermal insulation of its envelope. Attention should be drawn to designs that reduce the number of joints between the elements and, consequently, the number of potential thermal bridges. This approach can be identified in large, prefabricated modules of TECH 04 and Wikkelhouse.

Furthermore, the insulative effectiveness of different paper core materials can be compared. According to other researchers laboratory tests, the thermal conductivity of these materials ranges from U = 0.039 (W/mK) for cellulose fibre and U= 0.047 (W/mK) for A-flute corrugated cardboard, up to U = 0.125 (W/mK) for 50 mm thick honeycomb panel (see Table 10) (Čekon et al., 2017; Heyden & Lange, 2017; Meer, 2013; Russ et al., 2013; Salavatian et al., 2019). Honeycomb panels and corrugated cardboard can be produced from the same materials, therefore their environmental impact per weight is comparable. To achieve the reference thermal resistance of R = 1 (mK/W), it is necessary to use layers of various thicknesses and weights (see reference thickness and reference weight in Table 11). The lowest weight of the reference layer, and therefore the most efficient use of the raw material, is associated with cellulose fibre, used in the Tube Envelope. However, this type of insulation requires an additional enclosing structure that is filled in with fibres and would increase the total weight. Excluding the loose material, the best results were obtained with 2-layer A-flute corrugated cardboard and 12.5 mm and 25 mm thick honeycomb panels, however, the honeycomb layers are significantly thicker. In conclusion, it can be stated that 2-layer A-flute corrugated cardboard provides the most effective raw material use of all structural paper-based products analysed in the context of environmental impact. This material was used in the Wikkelhouse project.

TABLE 11 Selected properties of paper-based insulative materials

MATERIAL	TYPE	WEIGHT [KG/M^2]	WEIGHT [KG/M^3]	THERMAL CONDUCTIVITY [W/MK]	REFERENCE THICKNESS [MM]	REFERENCE WEIGHT [KG/M^2]
paper honeycomb panel 25 mm thick 12,5 mm thick	50 mm thick	1.80	36	0.125	125	4.50
	1.00	40	0.095	95	3.80	
	0.60	48	0.075	75	3.60	
corrugated cardboard A-flute, 3-layer C-flute, 3-layer BC-flute, 7-layer	A-flute, 2-layer	0.40	80	0.047	47	3.76
	0.55	110	0.047	47	5.17	
	0.50	125	0.053	53	6.63	
	0.70	100	0.050	50	5.00	
Cellulose fibre	-	-	40	0.039	39	1.56

The selection of the types of finishing materials and the method of laminating them to the core is another aspect considered. Aiming for recycling, it is crucial to not only use recyclable materials but also allow for their disassembly and separation. Although separable mechanical joints are more sustainable, they are often ineffective when used with paper-based materials, which are prone to local damage. The strongest bond between paper elements can be usually achieved with adhesives, which hinder the separation and recycling process. Therefore, the choice of joining method should be analysed individually for every project in order to ensure the highest possible level of recycling of the raw materials while maintaining the required mechanical properties. It is especially important to enable the separation of non-paper materials with high recycling potential, such as metal sheet facings.

Moreover, the use of composite materials, for which recycling process is much more challenging, should be avoided. This approach can contribute to reducing the amount of construction and demolition waste produced, which is one of the key challenges for the building industry (Pečur et al., 2020). The most easily recyclable finishing materials used in the analysed designs are steel or aluminium sheets (CATSE, TECH 04). Wood materials, as implemented in Wikkelhouse, have the lowest environmental burden, however, they require additional impregnation. Secondly, the most effective method to allow the materials to be disassembled is using mechanical joints or batten structures instead of adhesives (Crowther, 2000). This method was incorporated in CATSE and Wikkelhouse.

Finally, the proportion of virgin and recycled fibres in paper-based products influence the envelope performance. Virgin fibre can provide better mechanical properties and durability, while recycled fibre can reduce the material environmental impact (Asdrubali et al., 2016).

5 CONCLUSIONS

The presented analysis showed a variety of approaches to paper-based envelope design. It should be emphasised that most of the discussed envelopes were intended to be used in emergency and temporary architecture, which allows for some compromises in the design process. However, in permanent and semi-permanent buildings, greater emphasis should be put on ensuring sufficient thermal insulation, fire safety, and resistance to mechanical damage. Several completed buildings discussed in this article have proven that using paper materials in a building envelope is possible and can give satisfying results. However, in future projects, more emphasis should be put on the intentional selection of materials, techniques, and structures to make the designed envelopes as effective, durable, and functional as possible. This issue is crucial in terms of sustainable design since merely using paper in the structure of the envelope is no guarantee of reducing the environmental impact, however, it can be an important step towards this goal.

5.1 GUIDELINES AND SUGGESTIONS FOR DESIGNERS

The lack of extensive research and no material database significantly hinders scientists, engineers, and architects from conscious designing with paper products. The presented analysis can serve as the source of case-study-based information.

Based on the reviewed envelope examples, the following recommendations can be formulated for designers of environmentally friendly paper-based envelopes for semi-permanent buildings.

- The structure should consist of a paper-based insulative core and protective external layers, made of non-paper materials.
- The highest insulative properties with relatively small core thickness can be achieved by using cellulose fibres or multiplied 2-layers A-flute corrugated cardboard. The first material is blown-in and requires an additional structure.

- Panels should be ventilated to avoid damage due to condensation inside the paper structure. Breather membranes and cladding with an air cavity between them can be used.
- A double protection technique should be used to ensure surface water tightness. Durable finishing materials (metal, plywood, etc.) can be combined with polymer films, membranes, or varnishes. Water protection on the internal surface is equally important to prevent the envelope from becoming wet during normal use of the room.
- For users' safety, and often also due to legal requirements, the surface of the envelope should be fire-resistant, which can be achieved by using non-flammable finishing materials or fire retardants.
- In longer-life-span buildings, adequate protection against mechanical damage should be provided, as any surface damage exposes the core to moisture.
- Limiting the number of joints between envelope elements, and consequently, the number of potential thermal bridges increases the overall thermal effectiveness of the design.
- The envelope design should allow for separation and recycling of the different materials used, thus mechanical joints can be used between different materials if possible. It should be also considered that conventional mechanical joints (such as screws) are often not suitable for paper-based materials. Therefore it is advised to incorporate more durable materials e.g. wood in the joined area and avoid single-point connections.
- Particular emphasis should be put on adhesives, varnishes, impregnants, and film selection, as some of them can drastically increase the environmental burden of the design.
- The use of paper products made of recycled fibres should be considered, especially in non-load-bearing structures. In structural elements, the proportion of fresh and recycled fibres should be balanced to ensure the lowest possible environmental impact without compromising the mechanical properties of the element.

Paper-based building envelopes can be a step towards reducing the environmental burden of semi-permanent buildings. However, there is still a need for further research, especially regarding joining methods, pro-ecological impregnation techniques, and recyclability. Access to updated, research-based information is crucial for encouraging designers to use this material and make environmentally responsive design decisions. As a result, it may lead to the development of optimal design techniques and applications for paper-based products and enable their wider and effective use in the construction industry.

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