DOI: https://doi.org/10.38027/iccaua2023en0268

Paper-based Structures & Pop-Up Architecture: Challenges and Opportunities

*[1] B.A. **Mert Mısırlıoğlu** and [2] Assist. Prof. (PhD) **Mauricio Morales-Beltran**
Yaşar University, Faculty of Architecture, Turkey [1 & 2]
E-mail [1]: mert.misirlioglu98@gmail.com , E-mail [2]: mauricio.beltran@yasar.edu.tr

Abstract
Pop-up architecture encompasses ephemeral structures, built to be disassembled and reassembled. Among several available materials, paper is extensively used to build these temporary structures due to fabrication and sustainable reasons. Although by applying adequate production techniques paper can be used as a load-bearing component, its strength and durability might be compromised when exposed to environmental conditions. This paper aims at defining the challenges of designing and implementing paper-based structures, as well as at unveiling the potentials of using paper in pop-up architecture. In the first part, related literature and examples are reviewed to evaluate how rapid assembly, convenience of transportation, low-cost, less specialized labour in the production of components and in the assembly process, are parameters weighing in the choice of paper as structural material. The second part discusses selected case-studies, to show how paper-based components, connections, envelope insulation, transportation and assembly constraints are addressed to shape these temporary structures, thus becoming a source of inspiration for pop-up architecture.
Keywords: Pop-up Architecture; Paper-based Architecture; Paper Structures; Cardboard Construction.

1. Introduction

In contrast to traditional permanent architecture, temporary and pop-up architecture have the potential to offer explorations on experimental designs as they are not dependent on serving multiple purposes, environmental issues, and standard building regulations (Latka & Swieciak, 2021). Rather than experimental designs, architects often have to meet the requirements of building owners, funders, and users (Jasiolek, 2018). Temporary and pop-up architecture are open to the possibility of emphasizing a single purpose, intensifying its influence in pure designs. Pop-ups are structures that appear unexpectedly, operate temporarily, such as exhibitions, shops, small restaurants and pavilions; then disappear, after attracting a large number of customers and attention (Latka & Swieciak, 2021). In the designs of these structures, the chosen material and cost are as important as the structure itself. It can offer months or years of use, even permanently, depending on how the material is applied on the structure (Latka & Swieciak, 2021). Since this type of structures can change location or more likely be demolished after use, the most consistent approach is using materials that can be recycled and, thus, causing the least harm possible to the environment. The need to create a space for temporary purposes can be met with pop-ups (Latka, 2017).

The temporary use of the space or structure and their disappearance after its intended use, adds a new feature to the designs; the attractiveness of the things that can be accessed just for a limited time. These are mostly placed in unused or empty areas of the cities and rural areas, offering them a new and short-term identity (Latka & Swieciak, 2021). The possibility of experimental designs has been increasing its popularity among the designers, just as the exclusivity and time limitation features increase the popularity among users (Latka & Swieciak, 2021). These structures are made entirely from parts that can be assembled at the construction site, thus facilitating transportation and shortening the construction time (Carunchio et al., 2020, Amen, 2021; Aziz Amen, 2022; Amen et al., 2023; Amen & Nia, 2020).

Many types of materials can be used in temporary architecture: wood, concrete, and steel are common building materials to create structures wherein load bearing is a priority. Less conventional materials, such as paper, fabric, and plastics, are used to create structures wherein lightweight and ease of installation are rather important (Vectorworks, 2018). Since these latter ones are common features in pop-up installations, it is in harmony with this type of less conventional construction materials. Also, the use of lightweight materials facilitates transportation of the modular components of a structure to the construction site, and then assemble them. Apart from features of lightweight and easy-to-assemble, variables such as the location, purpose, and life-span, do affect the material selection and construction technique itself (Vectorworks, 2018). The structures used for temporary purposes, if not designed with suitable materials, might damage the environment during demolition, after completing their lifespan and purpose (Latka, 2017). From this perspective, paper can be considered as an example of a suitable material, since it has the advantage that it can be recycled with lower costs and use of energy (Latka, 2017).

The awareness of the factors threatening the environment started to increase simultaneously with the use of structural components that are compatible with nature, such as paper (Kanli et al., 2019). Considering that temporary architecture entails structures that exist for a limited time and purpose, it is important that make them recyclable and avoid non-recyclable waste as much as possible (Jasiolek et al., 2021). Being comparatively cheaper and light, paper can be used as building material, e.g., in temporary emergency shelters. The preliminary examples

of paper as a common design material in construction can be seen in traditional Japanese architecture, mostly as decorative, separator and sliding panels, but the use of it in architectural structures has begun to vary with the change and development of possibilities in paper production, e.g., cardboard and its types (Jasiołek, 2018).

1.1. Paper-based Architecture

The most common form of paper used as a structural component in architecture is cardboard. It is much heavier and more durable than standard paper. Although there is no clear distinction between standard paper and cardboard, it is also included under the paper category because it is based on cellulose fibres as a raw material (Diarte & Shaffer, 2021). The use of cardboard in architecture is often encountered in temporary and pop-up structures. Carboard is durable, recyclable, budget-friendly and a lightweight material (Latka & Jasiolek, 2022). Currently, the increasingly strong and diversified cardboard material has even been used as load-bearing elements in structures (Tütüncü & Ökten, 2021). For example, Shigeru Ban, a pioneer in this field of paper-based architecture, frequently uses paper tubes in permanent and temporary structures (Tütüncü & Ökten, 2021). Cardboards can also be produced as honeycomb panels, contains air gaps, which increases insulation capacity of any component made out of this material. The main setback of all cardboard products is that they are not resistant to fire and moisture, but this weakness can be eliminated with various varnish or coatings applied on its surface (Latka & Jasiolek, 2022).

2. Material and Methods

This paper aims at defining the challenges of designing and implementing paper-based structures, as well as at unveiling the potentials of using paper for either structural purposes or construction material, in the context of temporary and pop-up architecture. The main hypothesis put forward by this study is that it is possible to turn the challenges of paper-based construction —arising from the fragility of the material— into opportunities by becoming a source of inspiration to designers, who are otherwise reticent to use this material on a structural basis. For this reason, a literature review on examples of paper-based construction was conducted. The focus of this review was on temporary and pop-up architecture, where precedent studies on paper-based structures are common. Then, the related literature and examples are reviewed to evaluate how rapid assembly, convenience of transportation, low-cost, less specialized labour in the production of components and in the assembly process, are parameters weighing in the choice of paper as structural material. In the literature, there are case study studies and data for paper-based construction, including paper-based product types for construction, construction techniques, and joint types, which are adapted from those use with bamboo, wood and steel for connecting structural components.

Complementary to the opportunities and challenges arising from the literature review, it is fundamental to understand how these structures are built (Figure 1). Thus, the second part of this review examines three case-studies, selecting in consideration to the component types used and the joint types. to show how paper-based components, connections, envelope insulation, transportation and assembly constraints are addressed to shape these temporary structures, thus becoming a source of inspiration for pop-up architecture.

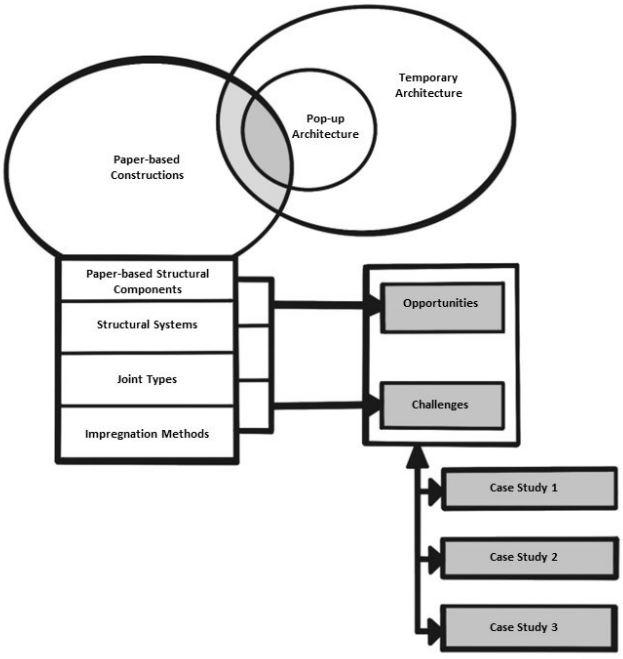

Figure 1. Structure of the study.

3. Construction with Paper-based Materials

3.1. Paper Products Used for Structural Purposes

Commonly, there are five types of paper-based products used in architectural structures, such as, paperboard, paper tubes, corrugated cardboard, honeycomb panels, L- and U-shaped profiles (Figure 2).

Paperboard: In the 19th century, it was first produced for the purpose of packaging and transporting products, and it is a paper type with density that can vary between 224 and 1650 grams/m2 (Latka, 2017). Paperboard types are chipboard, fibre board and solid board, which are defined according to production technique, density, layers and its application, e.g., structural or packaging purposes (Latka, 2017). It is also available in forms where it is finished with a waterproof liner (Sekulic, 2013). Although, it is a type with high strength among paper-based materials, but this strength depends on the orientation of the fibres of the produced material, the number of layers, and the applied adhesive (Cripps, 2004).

Paper tubes: This type can often be found as structural component in architecture. For example, after Shigeru Ban's designs; Its use became widespread and inspiration for the architectural designers to use paper-based components. (Tütüncü & Ökten, 2021). When paper tubes were first produced, they were used in the industries other than architecture, for the purpose of wrapping or transporting everyday items such as toilet paper, fabric, aluminium foil, stretch wrap, paper towels (Latka, 2017). After paper tubes began being used in construction, they were produced in different lengths and thicknesses. Tubes can be produced as parallel and spiral winding; which means wrapping up the layers, e.g., textile bobbins. Paper tubes with parallel winding are more resistant to loads than spiral ones (Bank-Gerhardt, 2016). The durability and strength of the tubes differ according to the production phase, winding and the quality of the paper that used in these processes. The efficient way to use paper tubes in architectural structures is achieved by using them as columns or beams in a single-storey, small-scale structures (Biermann, 1996).

Corrugated cardboard: It is common in the packaging, transportation, shipping boxes industry and was used for these purposes only until the early 20th century (Diarte & Shaffer, 2021). It consists of a corrugated paper core that is sandwiched between two flat paper surfaces (Latka, 2017). Mostly, made from recycled paper. The thickness of the corrugated core, also called fluting, varies between 0.8 and 4.8 mm (Latka, 2017). There are also versions of multiple corrugated cardboard that are laminated to make them even more durable and thicker (Diarte & Shaffer, 2021).

Honeycomb panels: It is a low-density paper type, which was invented in the 20th century as a result of searching for a lightweight and durable structural component (Diarte & Shaffer, 2021). It consists of three layers: an inner surface that combines two flat surfaces of paper and honeycomb-look alike core (Latka, 2017). It is used in architecture and interior architecture, and furniture design; as foam-based filling industrial materials, and in automobile production with glass-based coatings (Latka, 2017). Honeycomb panels are formed as a result of pressing the paper glued in layers, cutting the layers after the adhesive has dried, extending these layers to form hexagonal gaps, and sandwiching this honeycomb-shaped hexagonal core with two flat paper surfaces (Chen-Yan, 2012).

U and L shaped profiles: They are mainly used in transporting furniture, in order not to damage the edges of the furniture. It is produced by pressing and laminating the paper in layers in a U or L shapes (Pflug, 2000).

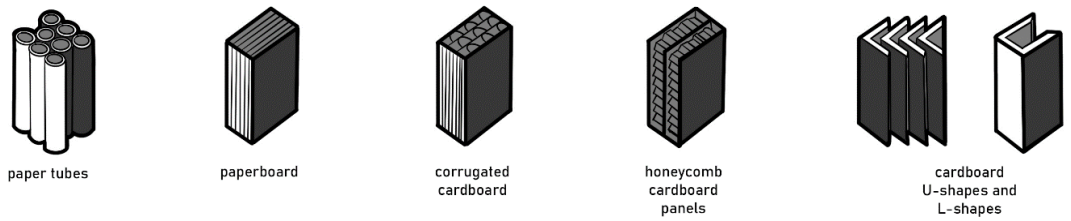

Figure 2. The five most common paper-based structural components used in temporary and pop-up architecture (Redrawn from Diarte & Shaffer, (2021); drawings by the authors).

4. Construction Techniques with Paper-based Materials

The possibilities are vast for developing techniques, assembly and structural systems that can be used for the paper-based component types, because there is no specific standard for structures using paper (Kanli et al., 2019). This allows other structural materials such as steel and wood to choose the most suitable joints from existing construction techniques and apply them to paper-based ones. The basic construction techniques for joints are basically divided into four groups: adhesive, flexible, mechanical fixations and form-fit joints (Figure 3). These are the basic joint types used in paper-based structural components, and joints with the same logic can also be used in cardboard tubes (Knaack et al., 2022). However, these joints are axial; They make the connection between the two components in only one of the *x*-, *y*- or *z*-axis (Knaack et al., 2022). Cardboard tubes have been examined separately from cardboard panel joints, as they can perform multi-axial joint connections as well as axial ones (Knaack et al., 2022).

Adhesive joints: In order to construct adhesive joints, lamination, couching or taping methods are available (Figure 3a). Lamination method is frequently used during assembly of components and polyvinyl or polyurethane based adhesives are used in order to provide strength and waterproofing. Starch-based glues are also preferred application, but they are not effective as PU or PVA (Knaack et al., 2022). The taping process is just as common as lamination (Knaack et al., 2022). It is especially used in structures that often need to be disassembled or prototypes that need to be built quickly (Knaack et al., 2022). Couching is similar to lamination. It occurs as a result of the combination of the paper-based layers and the fibres in them, which are exposed to high pressure and humidity, and then left to dry (Knaack et al., 2022). It is not used as often as the other two methods and is not developed enough, however; it is suitable for use in construction.

Flexible joints: It is a technique that is used for boards and thin panels that can be rigid and flexible at the same time, similar to the joints in fabric-containing structures. Applied for structures with thin walls and high tensile loads (Knaack et al., 2022). It is a joint type that requires snaps, such as riveting, punching or seam (Figure 3b). Making holes for the cables to pass through in order to create tension and being the base for the fixing process are done with the help of grommets (Engel, 2007). Rivets are also used to fix the surfaces to each other with the help of lapped connections. In order to prevent deformations such as breakage during and after such seaming operations, the stitch applied to thick layers should be short, and the stitch applied to thin layers should be long (Knaack et al., 2022). In addition, when gluing paper-based layers, care should be taken to use the durable side of the paper and seams applied at right angles to that direction (Knaack et al., 2022).

Mechanical fixations: These joints are mostly applied in wooden structures, but it can also be transferred to paper-based structures by adapting the standards and making certain arrangements (Engel, 2007). Selecting the optimum joint for the structure may result in a minimalist or complex result depending on the component's characteristics such as load-bearing capacity and resistance to environmental factors (Knaack et al., 2022). For example, nails are used in thick joints that are exposed to intense shear force. However, when the joints used are exposed to a tensile force, threaded screws should be preferred. Metal-based nails or screws are only suitable for use on high-density structural components (Figure 3c). Therefore, wood or plastic is generally used in paper-based ones (McQuaid, 2003).

Form-fit Joints: Frequently used in packaging and cardboard boxes. Joints made with various mechanical binders such as adhesives, nails or screws can cause paper-based components to lose their durability over time. As displayed in Figure 3d, joints created with form-fit techniques allow creating "puzzle-like" joints called "lap" between components (Knaack et al., 2022; Sumiyoshi & Matsui, 1991).

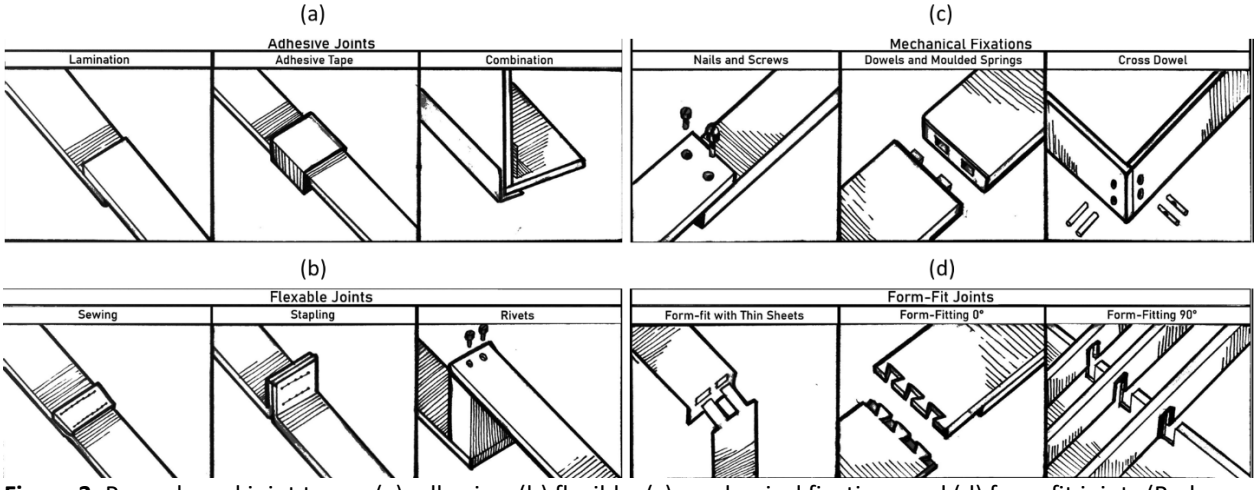

Figure 3. Paper-based joint types: (a) adhesive, (b) flexible, (c) mechanical fixations and (d) form-fit joints (Redrawn from Knaack et al., (2022); Drawings by the authors).

4.1. Frame Structure Systems for Paper Tubes

The structural components of the frames with load-bearing properties created by these techniques are entirely composed of paper tubes (Ban et al., 2014). The techniques used to construct with paper tubes were adapted from steel and bamboo constructions, so it is a separate system from other joints (Knaack et al., 2022). Contains multi-axial and linear assemblies that are created by different joint types. Linear assemblies include three types of joints; inner, outer sleeves and joints containing clamps or pressure profiles (Figure 4a). Also, as displayed in Figure 4-b, -c, and -d, respectively, multi-axials have three separate joint types, such as, form-fit, press-fit and sleeve (Knaack et al., 2022). Advantages of multi-axial and linear assemblies include ease of assembly and manufacture, however, the strength of the joints that are used in such assembly methods is limited due to the anisotropic and natural structure

of the paper (Knaack et al., 2022). Consequently, they are preferred in temporary and single storey structures such as in the Paper Log House design by Shigeru Ban (Ban et al., 2014).

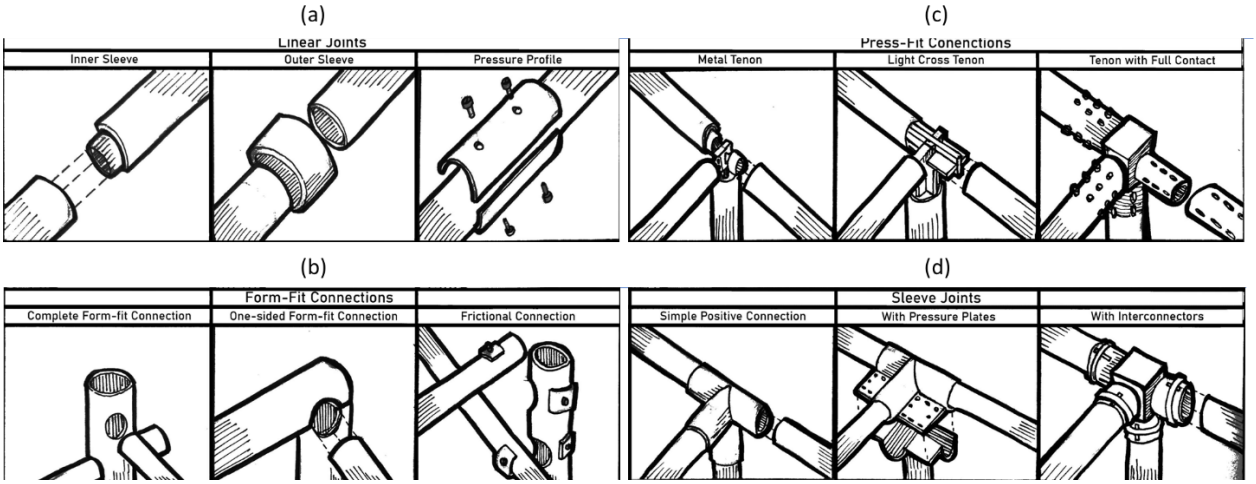

Figure 4. Joint types for construction techniques with paper tubes: (a) linear and multi-axial assemblies: (b) form-fit, (c) press-fit and (d) sleeve joints (Redrawn from Knaack et al., (2022); Drawings by the authors).

5. Challenges and Opportunities of Paper-based Construction

5.1. Fragility of Paper-based Construction and How to Overcome

Paper is a material mostly used outside the construction industry, and for non-structural purposes (Diarte & Shaffer, 2021). It is a recyclable material that can be produced in different sizes, homogeneous and reproducible; since it is renewable and accessible, people tend to use paper for decorative purposes or as separators, e.g., sliding doors (Latka, 2017). However, the reason of it is not a common material in constructions is; it displays a fragile image for most of the designers, because of its the weakness of the material against moisture and fire (Jasiołek, 2018). Besides, its physical and mechanical properties change depending on the direction; that is, the strength of the paper-based material surface is differs in the x, y and z axis, yet this feature, called anisotropy, might become an advantage thanks to the developed technology. Trees are used in the production process, and the raw material is called pulp; it is a near-liquid form of cellulose fibres and is obtained from raw wood. Thus, paper can be seen as an evolved and improved form of wood as a result of these developments (Knaack et al., 2022). Also, many, if not all, of paper's weaknesses as a building material are related to its bond to wood, but the experience that has been gained through wood constructions can be used to overcome these weaknesses in paper-based structures as well. Wood has different physical strength in each aspect of its surface due to the long and natural growth process of the tree; meanwhile, the damage that the tree receives during the growth process creates the character of the wood (Latka, 2017). The fact that people have been using wood in their buildings over the years has led to its structural consideration and sufficient knowledge about its safe use in constructions (Kanli et al., 2019). Lamination method can be given as an example; it is a development that took place in order to compensate for the anisotropy of wood. It is a method that occurs as a result of gluing wooden boards by overlapping each other in the opposite directions and each layer covers each other's defect (Latka, 2017; Knaack et al., 2022). Each of the wooden boards has individual strengths in the *x*-, *y*- and *z*-axis and the purpose of the lamination process is to balance the axes that have these separate strengths with each other, so lamination is a method that can be used to strengthen paper-based structural components. (Latka, 2017; Knaack et al., 2022).

Wood and its derivatives can absorb water and release it in the same way and damage from these events can be reduced with the right production methods and chemical components (Latka, 2017). Considering the fire protection of wood, it has the possibility of losing its integrity due to the charring of its surface and other layers during combustion and greatly reducing the rate of complete combustion. In this respect, the behaviour of paper is the same and the burning process can be slowed down by thickening the layers, but the cost and material usage will be more. However, for paper, it is much more difficult to resist moisture than fire protection. Moisture damages the structure of the paper in terms of size and rigidity. If a thin sheet of paper gets wet, it ripples and degrades irreversibly. Since paper-based products are mainly used for purposes such as packaging rather than being used in construction, and it is important that the transported products should not contact with liquids, the production of various additives and their application on paper have significantly increased their resistance to water. This development has enabled the use of paper-based products in architectural structures (Knaack et al., 2022).

5.2. Impregnation of Paper-based Structures

When constructing architectural structures with paper-based materials, the considered things are resistance to moisture and water, behaviour against fire, permeability to biological factors and gases (Kanli et al., 2019). The aspect that is emphasized in literature as the biggest weakness of constructing with paper is its lack to resistance to moisture; the hydrogen bonds in it separate from each other when exposed to moisture or water, and also, some substances in the air can cause paper to become even more fragile (Kanli et al., 2019; Knaack et al., 2022; Latka, 2017). At the same time, since it consists of cellulose, a plant-based raw material, it could be a living space for microorganisms; this feature shows the biocompatibility of the material and is an advantage that cannot be ignored, but, considering that paper will have a structural function, its direct contact with the ground and air may reduce its durability (Knaack et al., 2022). In addition, it is possible to ignite quickly due to its surface consisting of fibre webs. However, these weaknesses can be overcome with some additives and construction techniques, then paper can become a durable building material (Jasiołek, 2018).

Resistance to water: Substances that increase the water resistance of paper-based materials work by chemically bonding the surface fibres to be water-resistant; since tea bags, coffee filter papers and towel rolls must have high water resistance, they are produced with substances that resist (Knaack et al., 2022). For construction, the durability of water-resistant papers, which can be determined by subjecting them to tensile tests, should be at least 15% of their dry state with additives, e.g., formaldehyde-based resins are often preferred among chemicals that increase resistance to water. (Knaack et al., 2022; Latka, 2017).

Sizing of paper: Paper is hydrophilic by nature and absorbs water during contact with any liquid. Reversing this phenomenon, blocking water, slowing it down and making the paper-based material hydrophobic is called sizing (Knaack et al., 2022). This process can be performed by either adding resin-based adhesives into the pulp (internal sizing) or applying the active chemical substance only to the surfaces of the paper (surface sizing) (Knaack et al., 2022). Even if these two processes make the material surface hydrophobic, it cannot maintain this effect permanently and it will get wet after a while. For this reason, a more effective and common method is the lamination of paper with polyethylene-based plastics. However, care should be taken of not deteriorating the material nor compromising its recyclability, during this plastic lamination method (Jasiołek, 2018).

Protection against microorganisms: Under certain circumstances, cellulose might become a shelter for microorganisms and this causes the cellulose to biodegrade, thus losing its rigidity (Knaack et al., 2022). In order to prevent the destruction of the paper-based material by microorganisms, methods similar to wood are used. The common active chemical components applied are disinfectants, rot inhibitors, preservatives and pest inhibitors (Knaack et al., 2022).

Protection against fire: Paper is exposed to burning due to its fibre structure, but it is possible to increase fire resistance, prevent ignition, or disrupt fire by various methods (Latka, 2017). Fire retardants such as, halogen, silicate-based, nitrogen and phosphorus, are used divided into combined, physical and chemical according to the mechanism they are triggered in order to prevent ignition. The main purpose is to interrupt the oxygen diffusion on the material surface (Knaack et al., 2022).

6. Case Studies

6.1. Selection Criteria for Case Studies

Constructions produced with paper-based materials have challenges rather than disadvantages. Each challenge is an opportunity waiting to be turned into an advantage. Among the most fundamental challenges of the inclusion of this material in constructions is its instability against water and fire, and therefore creating a fragile perception among designers who consider choosing paper. However, these and all the other challenges can be turned into an advantage with various applications and the right techniques. Each of the case studies selected represents at least one opportunity to use paper-based materials for structural purposes. For example, Instant Home took the light-weight and foldability of paper as an opportunity and turned this into an advantage. On the other hand, Paper Log House preferred ease of assembly; It is a design that can be constructed by 3-4 people in 5-6 hours, even without professional help, by using the paper components available in every country and the local materials of the region where it will be built, so that disaster victims can reach a shelter as soon as possible. Besides, L'elephant Pavilion has managed to survive for about one year with its cardboard tube columns placed on a quarter-circle wooden base. Efficient use of material that created with the design itself was an opportunity that turned this into an advantage for the case. Selected case studies have addressed some of the challenges and how those succeeded in overcoming them as well as opportunities. For example, Instant Home has provided its water resistance and foldability with adhesive joints. Paper Log House has used and strengthened paper as a hybrid of wood and steel in parts such as floors and walls where paper-based components may be weak. In addition to the robustness of its structure, L'elephant Pavilion has shown resistance to environmental conditions for a long time thanks to the impregnation method applied on its components. In other words, these three case studies have been chosen to highlight the most

basic opportunities of paper-based structures, while describing how their most basic challenges can be turned into advantages.

6.2. Instant Home

The project, developed by TU Darmstadt, required to be quickly assembled and disassembled, lightweight and easy to transport, in order to provide a temporary shelter module after natural disasters. For these reasons, the project was mostly based on paper-based materials (Knaack et al., 2022). After an initial design proposed by students, a foldable design was selected (Figure 5) as this project featured a rapid installation, and benefited from lightness and flexibility (Knaack et al., 2022). For the mass production and further development, the concept with shipping container dimensions was preferred, afterwards a prototype was built so that tests can be carried out on it and large-scale deployments to disaster-affected areas (Knaack et al., 2022). When this structure, which looks like a flat surface when folded, is unfolded, extends to the size of a shipping container, the panels remain stable through to the ribs that supports these panels and a foldable panel placed in the core of the structure with the task of dividing the room (Knaack et al., 2022). Vertical and horizontal ribs are connected to each other at the corners of the container; this provides the rigidity of the walls and ceiling and between each of the components of the building, there are adhesive joints in order to provide waterproofing and foldability feature (Knaack et al., 2022). Support wall racks are also used to improve stability and stiffness against deformations that may be caused by situations such as buckle. The concept, which includes a single room, has a floor size of 2.28 meters by 5.80 meters when unfolded, and a height of 2.20 meters, but in the folded form, the floor size is reduced to 0.30 meters by 5.80 meters, and the height remains the same (Knaack et al., 2022). When this structure changes to folded form, it can fit in a standard size ISO container with five more modules together with it. What makes Instant Home instant and provides rapid assembly is the unique joint design. Also, it meets the easy portability requirement it aims for.

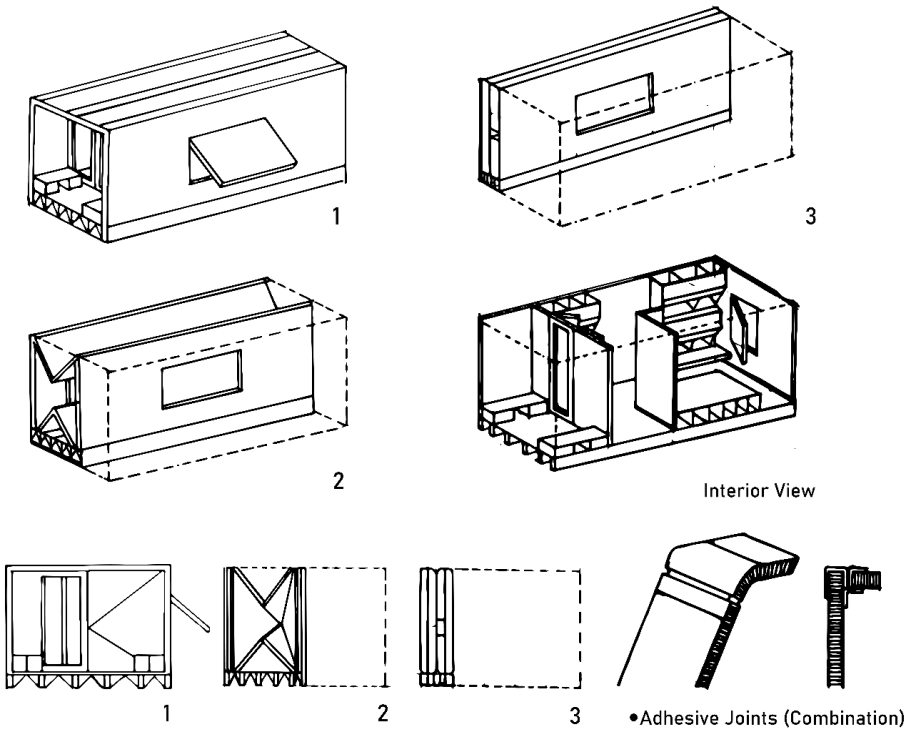

Figure 5. Instant Home fold and unfold process (Redrawn from Knaack et al., (2022); Drawings by the authors).

6.3. Paper Log House

Shigeru Ban founded the Voluntary Architects' Network in 1995, which focuses on helping victims of natural or man-made disasters (Ban et al., 2014; Latka, 2017). The first paper-based emergency shelter project that Ban designed and built in cooperation with this organization, is the Paper Log House (Figure 6), which was used after the 1995 earthquake in Japan (Ban et al., 2014; Latka, 2017). Cardboard tubes with a diameter of 108mm were used extensively on the walls, floor and roof of this 36m^2 housing (Latka, 2017). The foundation of the structure consists of beer crates filled with sandbags, and a floor contains cardboard tubes and plywood plates is added on top of this foundation (Ban et al., 2014). With the help of plywood pegs, cardboard tubes were fixed on the floor to form a wall, and the tubes were attached to each other with adhesive tapes and reinforced with steel rods placed horizontally inside them (Ban et al., 2014). Before the roof was placed over the walls, a square plywood frame was added between the roof and the tube walls (Ban et al., 2014). The connection between the components of the roof is provided with light-cross tenon plywood joints and a PVC membrane is stretched to the roof frame for waterproofing

the structure (Knaack et al., 2022; Ban et al., 2014). After the completion of the construction process, a polyethylene-based coating was applied on the cardboard tubes in order to increase their moisture and water resistance (Latka, 2017). This design was also used in other disasters after the great earthquake in Kobe, Japan in 1995, and its design has changed according to the climate and local materials of the region where it will be built (Ban et al., 2014). The construction of a module can be completed in about 6 hours with the cooperation of 2-4 people, without professional help and equipment (Latka, 2017).

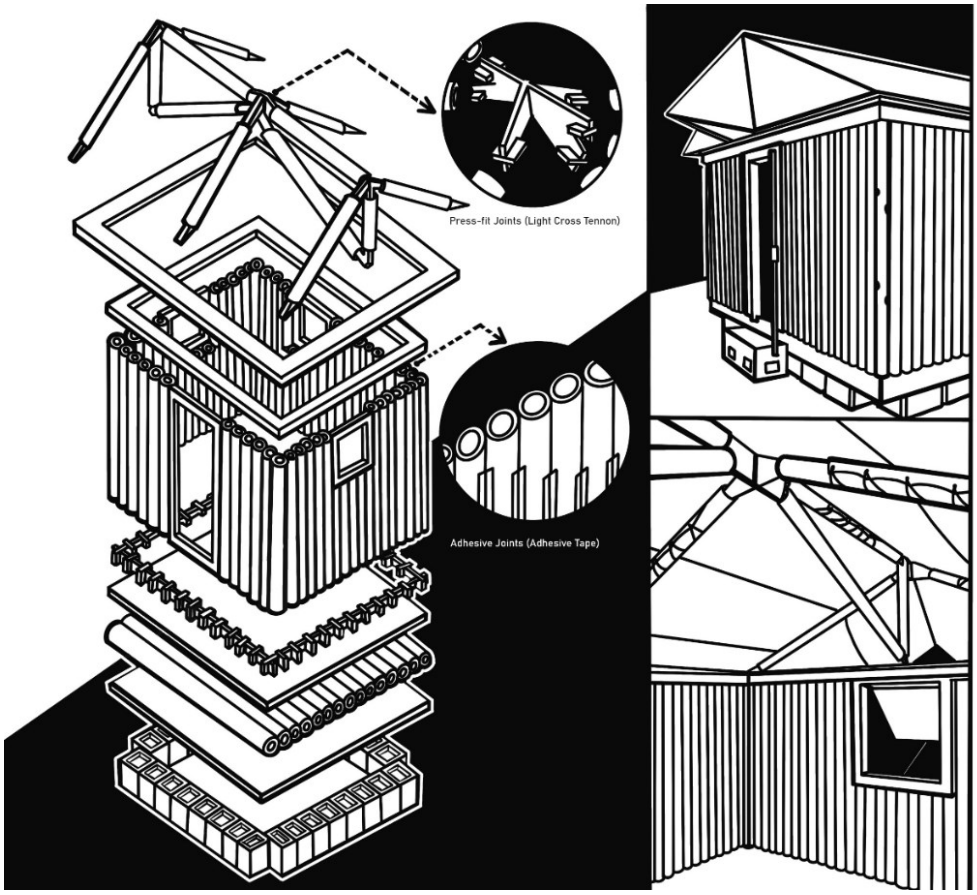

Figure 6. Exploded axonometric of Paper Log House, 1995 Kobe version
(Redrawn from Ban et al., (2014); Drawings by the authors).

6.4. L'elephant Pavilion

Displayed in Figure 7, L'elephant Pavilion is a student project that designed and built as a part of the CREATE Summer School and ProtoLab Workshops organized by the Faculty of Architecture at Wroclaw University of Science and Technology. The timber components at the foundation of the L'elephant Pavilion had 14x130cm size, and are bolted to each other in halved pieces which creates a quarter circle as a result. Wooden cylindrical caps have been added to the connection points of timbers in a way that cardboard tube columns can sit on these points. Chipboard joints attached to the columns with pipe clamps at regular intervals in order to add three beams between each of the two columns, after a total of 10 cardboard tube columns of 2.5 and 2m lengths mounted on to the caps. There are L-shaped cross tenon joints formed by interlocking the plywood pieces that are specially designed for the purpose of combining the cardboard tube components used for the roof. As it is placed on columns with different heights from each other; the roof has a recessed appearance when viewed from the entrance of the pavilion. A total of 32 honeycomb cardboard panels with colour were hung on the beams on one side of the structure, eight between each column, with the help of zip ties. On the other side, fabric threads were stretched to match the colours of the opposite panels and applied to the roof in the same way. Paper-based components of the pavilion are impregnated by using polyurethane liquid varnish. It has been exhibited for approximately one year; its beams, panels and fabric threads were damaged in that time, but still maintain their structural rigidity.

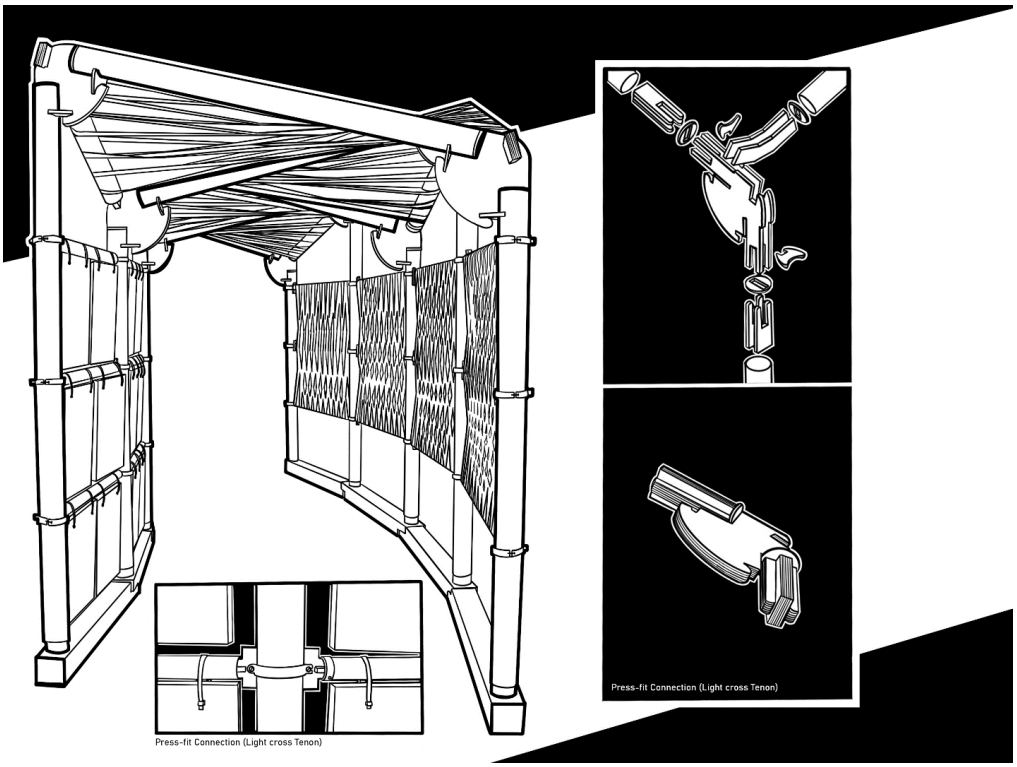

Figure 7. L'elephant Pavilion front view, plywood and chipboard joints
(Redrawn from the photos by authors & Jerzy Latka; Drawings by the authors).

7. Discussion

The main scope of this research with the literature review is to discover the opportunities and challenges of using paper-based materials as structural components in temporary and pop-up architecture. Thus, it aims to present cases and literatures in that field of architecture as evidence to prove that these challenges can be overcome with certain construction and impregnation techniques. The opportunities and challenges of paper-based structures, which can be summarized from the literature review, are mainly:

7.1. Opportunities

- With pulp being the main material in paper production with the developing technology, more paper can be produced with less material. It became even more budget friendly.
- Paper is frequently in use as disposable daily life products highlights its features such as being cheap, available and recyclable.
- The fact that people have been using wood in their buildings over the years has led to its structural consideration and sufficient knowledge about its safe use in constructions and also, this knowledge can reflect to the paper-based constructions.
- Anisotropy of paper is an advantage with the developed technology. Lamination is an example to those developments. It is a method of gluing wooden boards that has been cut and overlapping each other in the opposite directions and each layer covers each other's defect.
- The ability of chemical separation and recombination of the fibres in the paper itself is one of the greatest advantages of paper as a construction material. Therefore, it is a material that can be produced in different sizes, homogeneous and reproducible.
- For wood as a construction material, other layers of a laminated piece during combustion, carbonization greatly reducing the rate of complete combustion. In this respect, the behaviour of paper is the same and the burning process can be slowed down by thickening the layers.
- Since paper-based products are mainly used for purposes such as packaging rather than being used in construction, and it is important that the transported products do not come into contact with liquids, the production of various additives and their application on paper have significantly increased their resistance to water. This development has enabled the use of paper-based products in architectural structures.
- Cardboard types can also be layered according to different load carrying needs. Contrary to their lightweight, they form structurally highly efficient sandwich components.

- One of the features that makes paper attractive for use in temporary structures is its lightweight. To ensure movability and reusability in temporary structures lightness and ease of transport are essentials and paper is a material that meets this requirement.
- Paper tubes, which can be seen in Ban's designs, is not a flexible material that can be curved in normal conditions, but arch or bent structures can be created by cutting them in certain sizes and bringing them together with connectors or it can bend with wet shaping like in the wood construction components.

7.2. Challenges

- In the paper production the most frequently used plants are trees but in fact it can be produced not only from trees, it can be produced with any plant that contains cellulose as a raw material. Although it seems like an opportunity at first glance but its excessive consumption will harm the environment.
- Meanwhile, the damage that the tree receives during the growth process creates the character of the wood that obtained. Therefore, this emphasizes that each wood that obtained is different from the other and cannot be standardized.
- The reason of it is not a common material in constructions is because it has a fragility for most of the designers. This fragility is due to the weakness of the material against water, moisture and fire. Considering the fire protection of wood, it has the possibility of losing its integrity due to the charring of its surface. Moisture damages the structure of the paper in terms of size and rigidity, and it becomes unstable. If a thin sheet of paper gets wet, it ripples and degrades irreversibly.
- The structures used for temporary purposes and for a period of time, if that are not designed with suitable materials, they damage the environment when those structures get demolished after completing their lifespan and purpose.
- Impregnation methods can adversely affect the paper being a recyclable and environment friendly material. More research and practice needed in this regard.

8. Conclusions

While determining the opportunities and challenges of the use of paper-based materials in architecture; various sources that are including the relationship of paper with wood, types of paper-based products that can be used for structural purposes, construction techniques for these materials, impregnation methods against external factors were examined and case studies were selected to support the results obtained. Although paper cannot replace the frequently used materials in traditional permanent architecture, such as steel, wood and concrete; it has the opportunity to be indispensable for structures that require practical solutions, lightweight, transportability, low-budget and recyclability in temporary and pop-up architecture.

8.1. Final Remarks

The use of paper-based components in construction has high potential and advantages such as, recyclability, lightweight, foldability e.g., origami, and low-cost compared to traditional construction materials, the experiences gained in wooden construction are transferable to the paper structures (e.g., joint designs and impregnation techniques). Nevertheless, its low-resistance to water and fire is among its most well-known challenges, but it can gain fire resistance due to carbonization when it is produced in layers or with fire-retardants. Besides, water, moisture resistance can be ensured with PU or PVA based coatings. Also, there is a feature that can be both count as an opportunity or challenge; cellulose being a biodegradable raw material. All these features, opportunities and challenges can be observed in the literature review and case studies.

There is a situation, however, that may become an obstacle rather than a challenge; the paper is produced mostly from trees, the fact that each tree is unique and as a result of that, each paper produced is different from each other in terms of anisotropy and strength, because of this; paper-based materials could not be standardized completely for construction. Even if paper-based structural components are not fully standardized, there are certain standards in temporary architecture and paper structures that can comply to it. For example, providing resistance to fire, moisture and water is a must because these are the factors that will affect the rigidity of the material. Even if this is an obstacle, it is not an obstacle that cannot be overcome with ease.

Apart from this, even if the paper-based construction has many examples both in literature and practice, especially in temporary architecture; it does not have enough to make construction standards. To ensure that, to diversify the literature and increase the designs in practice; more designers should take into an account the experimentation and opportunities offered by the paper-based materials. Moreover, is necessary to work on issues such as more environment friendly impregnation methods, increasing recyclability and designing new joint types.

Acknowledgements

The authors would like to thank Julia Kutera, Julia Myślińska, Martyna Apczyńska, Kinga Wasilewska, Borys Oleński, and Kiryl Furmanchuk for kindly sharing the construction drawings of L'elephant Pavilion.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of Interests

All authors contributed equally to the article. There is no conflict of interest.

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