CCC 2025 **Proceedings of the Creative Construction Conference** (2025)
Edited by: Miroslaw J. Skibniewski & Miklós Hajdu & Žiga Turk
https://doi.org/10.22260/CCC2025/0006

SMALL RESIDENTIAL UNIT MADE OF PAPER-BASED PRODUCTS - RESEARCH AND DESIGN

Paweł Niewiadomski, Anna Karolak, Jerzy Łątka
Wroclaw University of Science and Technology, Wroclaw, Poland

Abstract
Growing market of construction industry as well as limitations in access to basic building materials such as timber, steel, and cement force engineers to use alternative building materials. At the same time because of natural disasters and wars there is a need of building mobile, non-expensive, easy and quick to assemble emergency shelters. The answer for the above mentioned issues may be paper-based products which seem to be promising building material. In this paper research on the potential use of paper-based products, namely paper tubes to create a small residential unit has been presented. For this purpose mechanical parameters of paper tubes were tested. Compressive, tensile, and flexural strengths were determined. Because of non-isotropic character of material and scale effect similar to what can be observed in the case of timber structures, mechanical tests were conducted both on small specimens and on full-scale elements. Based on test results and architectural layout structural design has been done. In calculations basic assumptions, static scheme, dead and live loads, loads combinations, internal forces and dimensioning have been included. Finally, considering aspect of low-costs, sustainability, easiness in assembly and mobility design of small residential unit has been created.

Keywords: design, mechanical properties, paper-based products, paper tube, residential unit.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2025.

1. Introduction

Nowadays, a growing interest in sustainable development in construction building is observed. More and more alternative structural solutions and unconventional, alternative building materials are applied, which is often connected with limitations in access to conventional materials, such as timber, steel or cement. At the same time because of more and more frequent natural disasters, such as floods, hurricanes, earthquakes and human-made disaster, such as wars, there is a visible need of building emergency shelters, which are mobile, easy and quick to assemble and above all non-expensive. Such objects are often made of alternative building materials. One of the materials, that is increasingly common and, in addition, eco-friendly, is paper. It turns out, that paper-based products may be used as building components.

Paper is a very interesting material with a wide range of applications [1], the material that seem to be a promising building material in construction in terms of its strength parameters [2, 3]. Paper-based components have been already applied in construction, for example paper tubes used as beams and columns in frame structures [1, 4, 5]. At the same time, there are only a few works presenting the description and the results of experimental research of paper tubes [6, 7, 8]. The values of compressive, tensile and bending strength obtained in the above mentioned tests were equal more less to several MPa, depending on the dimensions of the paper tubes. A broad review of research on the above mentioned elements is presented in the paper [3]. The researchers studying this topic agree that paper tubes can be applied as load-bearing elements (with appropriate assumptions). However, there is still need to investigate the subject.

In this paper, the experimental research results along with the static analysis are presented. They were conducted at the Faculty of Civil Engineering at Wrocław University of Science and Technology. The main objective of the research and analysis was to confirm the possibility of the use of paper tubes as

Corresponding author email address: pawel.niewiadomski@pwr.edu.pl

structural elements. Then, a design of a small residential unit was created on the basis of the obtained results. As a last part of an ongoing project small residential unit will be assembled with paper tubes as structural elements.

2. Materials and methods

In order to determine the parameters of compressive strength, tensile strength and flexural strength, experimental tests were performed on small samples of paper tubes. Three types of paper tube samples were tested:

1) with an outer diameter of 60 mm, a wall thickness of 4 mm (‘tube 60’);

2) with an outer diameter of 115 mm, a wall thickness of 7 mm (‘tube 115’);

3) with an outer diameter of 170 mm, a wall thickness of 10 mm (‘tube 170’).

For the compression tests small samples of paper tubes with a height equal to twice the outer diameter of the tube were used (Fig. 1 a)). For the tension tests special samples of oar shape were prepared with the length of 300 mm and the width at the point of narrowing of 24 mm (Fig. 1 b)). For the flexural tests samples with the length of minimum of at least four times tube diameter were prepared (Fig. 1 c)). In this case samples were subjected to 3-point and 4-point bending tests.

Then, in order to verify the values of the obtained parameters, tests on elements in technical scale (4-point bending tests) were performed (Fig. 1 d)), as in the case of paper the scale effect may appear and it must be considered, similarly as in the case of wood. Two types of tubes were tested:

1) with an outer diameter of 190 mm, a wall thickness of 10 mm (tube 190),

2) with an outer diameter of 200 mm, a wall thickness of 15 mm (tube 200).

The length of the tubes in both cases was as it was assumed in the design, equal to 2500 mm.

Paper tubes were prepared by Corex and had density of 650 kg/m3.

Samples moisture, which is a crucial parameter in the case of paper-based products, affecting the behaviour of the material, was controlled during tests and it was at the level of 7 ± 0,5%.

The tests were performed at the Faculty of Civil Engineering at the Wrocław University of Science and Technology by the use of the MTS 810 hydraulic press and ZD 600 hydraulic press.

The testing procedures applied in this case were on the basic of the testing procedures for wood according to the standards, assuming the analogy of wood and paper-based products behaviour. The views of the exemplary samples (small and full-scale) during the tests (compression, tension, bending) are presented in the Fig. 1 below.

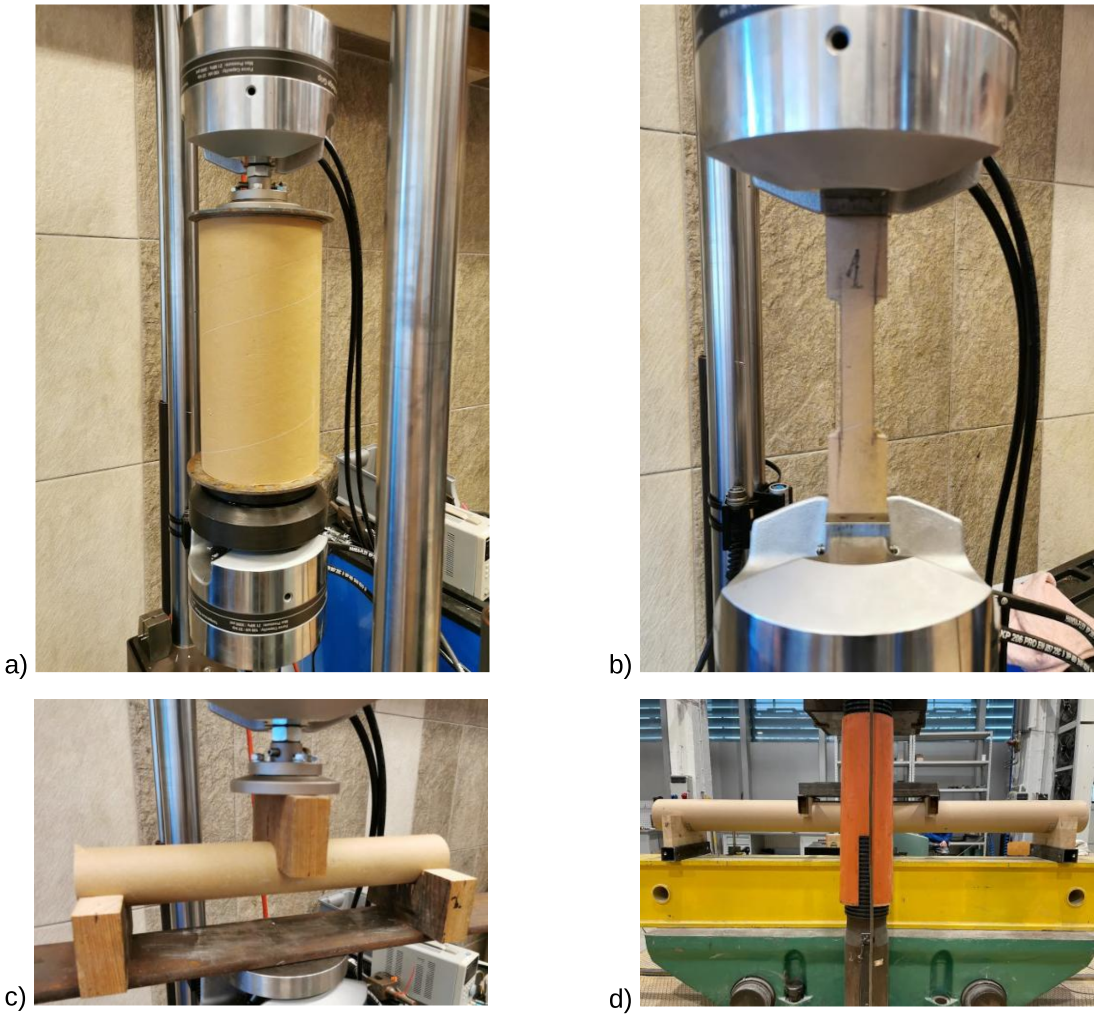

Fig. 1. The views of the samples during the tests: a) compression test, b) tension test, c) 3-point bending test, d) 4-point bending test on a full-scale sample.

3. Results and discussion

The overall research results for the small samples from compression tests, tension tests and bending tests – the calculated strength parameters for these samples are presented below, in Tab. 1.

Table 1. Calculated strength parameters for the small samples.

Sample type	Mean compressive strength $f_{c,mean}$ [MPa]	Mean tensile strength from tension test $f_{t,mean}$ [MPa]	Mean flexural strength form 3-point bending test $f_{m3,mean}$ [MPa]	Mean flexural strength form 4-point bending test $f_{m4,mean}$ [MPa]
Paper tube 60	9.91	12.80	11.78	14.86
Paper tube 115	11.09	12.27	12.91	11.69
Paper tube 170	5.70	8.72	5.81	6.42

Results for full-scale elements are presented as follow. Exemplary load – deflection plot for a full-scale element (tube 200) in 4-point bending test is presented in Fig. 2 and the values of calculated flexural strength obtained in the bending tests are presented in Tab. 2.

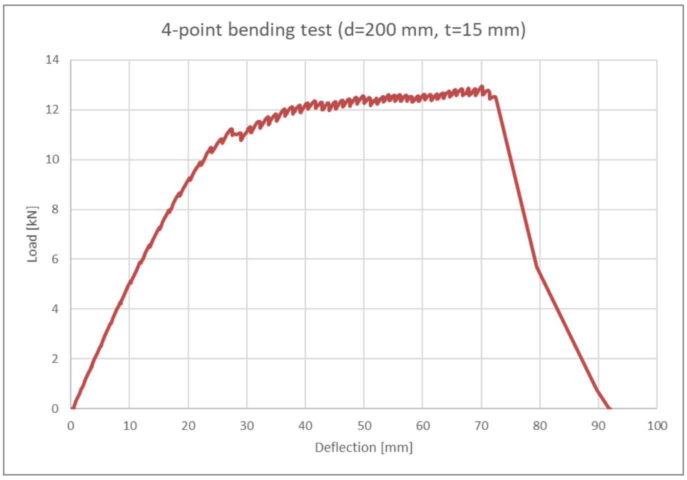

Fig. 2. Exemplary load – deflection plot on 4-point bending test for the full-scale element.

Table 2. Calculated strength parameters for the full-scale samples.

Sample type	Mean flexural strength form 4-point bending test $f_{m4,mean}$ [MPa]
Paper tube 190	10.85
Paper tube 200	12.09

Considering above presented results it may be observed that in case of flexural tests there is significant difference of obtained values of flexural strength for small and full-scale samples. When comparing tube 170 with tube 200 and considering 4-point bending test the difference is equal to approx. 88%. This confirms scale effect in paper based products, similar to timber elements, and emphasizes the importance of conducting full-scale testing of components.

4. Design

4.1. Architectural design

Small residential unit serving as emergency shelter need to meet several conditions such as: easiness and quickness to assembly, low cost, sustainability, and resistance to weather conditions. To satisfy all above mentioned conditions basic design of a small residential unit has been prepared and shown in Fig. 3.

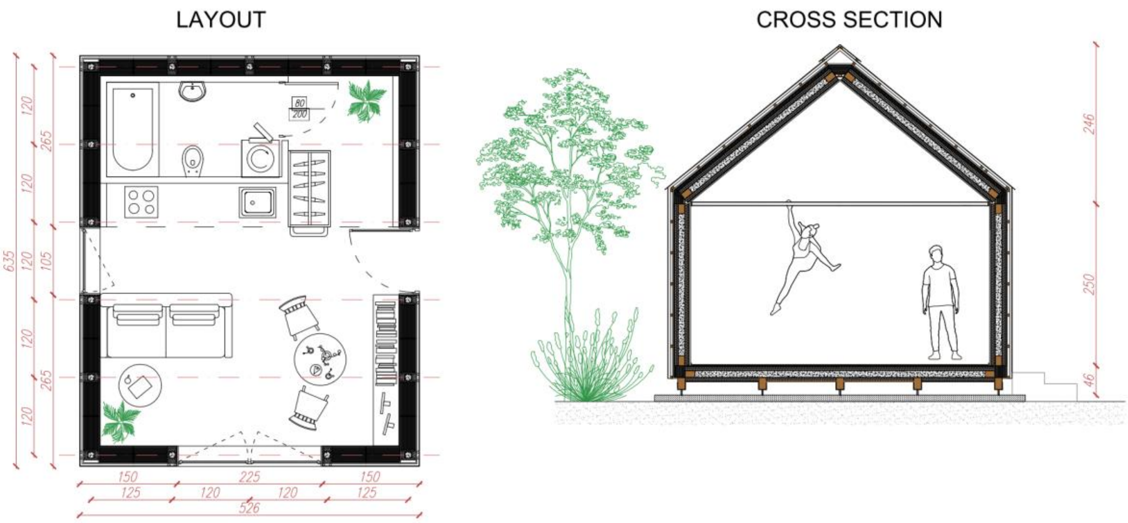

Fig. 3. Layout and cross section of small residential unit.

Most important features of the residential unit are following: gross area < 35 m^2, structure of the floor, wall and roof claddings made out of paper-based products, building structure separated from ground to prevent paper-based cladding against moisture.

4.2. Structural verification

Structural verification has been done based on following steps. First static scheme has been identified (Fig.4 a)). Rods no. 1-4 have been assumed to be tube 200, whereas rod no. 5 is a #20 mm steel rebar. Frame spacing equals to 1.20 m. Supports and all of the connections except steel rod have been assumed to be fixed. Next, loads according to Eurocode 1 [9] were applied, including dead, live, snow and wind loads. Loads combination have been prepared according to Eurocode 0 [10], and min/max internal forces, namely bending moment (Fig. 4 b)) and axial force (Fig. 4 c)) have been determined.

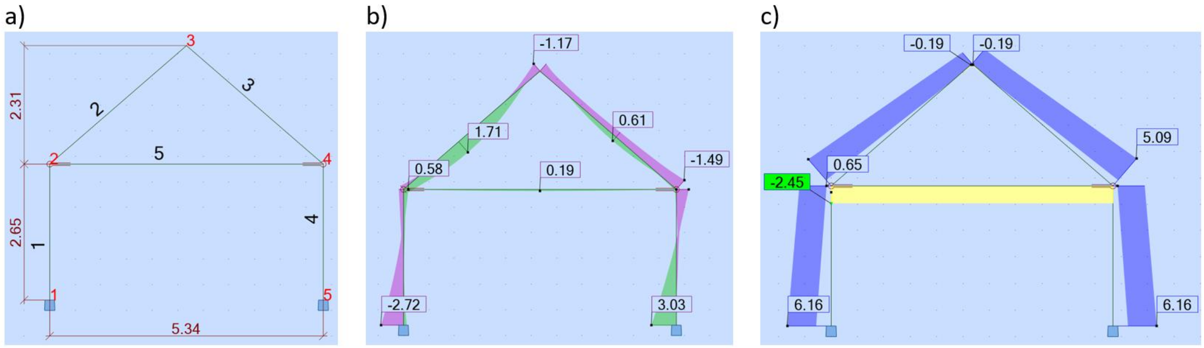

Fig. 4. a) static scheme, b) min/max design bending moment, c) min/max design axial force.

Finally, stress check calculations similar to timber structures described in Eurocode 5 [11] have been done. Characteristic flexural and compressive strength have been assumed based on test results described in previous chapters. Factors k_{mod} and γ_m have been adopted based on Eurocode 5 [11]. Out of plane buckling factors have been neglected as frames are connected with OSB plates, and thus protected against buckling. Design bending strength $f_{m,d}$, design compressive strength $f_{c,d}$, design bending stress $\sigma_{m,d}$, design compressive stress $\sigma_{c,d}$, and final utilization ratio UR have been calculated according to equations 1-5.

$$f_{m,d} = \frac{f_{m,k} \cdot k_{mod}}{\gamma_m} \quad \text{(eq. 1)}$$

$$f_{c,d} = \frac{f_{c,k} \cdot k_{mod}}{\gamma_m} \quad \text{(eq. 2)}$$

$$\sigma_{m,d} = \frac{M_{Ed}}{W} \quad \text{(eq. 3)}$$

$$\sigma_{c,d} = \frac{N_{Ed}}{A} \quad \text{(eq. 4)}$$

$$UR = \left(\frac{\sigma_{c,d}}{f_{c,d}}\right)^2 + \frac{\sigma_{m,d}}{f_{m,d}} \quad \text{(eq. 5)}$$

Summary results of structural verification have been gathered in Table 3.

Table 3. Structural verification results.

Design bending moment	Design axial force	Section area	Section modulus	Characteristic bending strength	Characteristic axial strength	Load duration and moisture influence on strength factor
M_{Ed} [kNm]	N_{Ed} [kN]	A [cm^2]	W [cm^3]	$f_{m,k}$ [MPa]	$f_{c,k}$ [MPa]	k_{mod} [-]
3.03	6.16	87.2	375.4	12.09	5.70	0.9
Material factor	Design bending strength	Design axial strength	Design bending stress	Design axial stress	Utilization ratio	
γ_m [-]	$f_{m,d}$ [MPa]	$f_{c,d}$ [MPa]	$\sigma_{m,d}$ [MPa]	$\sigma_{c,d}$ [MPa]	UR [%]	
1.3	8.37	3.95	8.07	0.71	100	

5. Summary and conclusions

- Laboratory tests on small samples and full-scale samples were performed in order to determine the strength parameters of paper tubes. The results of the tests confirm that in the case of this material a scale effect appears and for this reason, in addition to tests on small samples, tests on full-scale elements are recommended.
- Further research is planned in the future to obtain an accurate, more detailed picture of the static work of the material. The direction for the future should be laboratory tests on full-scale elements.
- Based on the preliminary research results presented in the paper, a structural analysis with verification was conducted, which confirmed that the tested elements can be used as load-bearing elements for the construction of a small residential unit. Such a unit has been designed and a prototype will be assembled in the near future.

Acknowledgements

This research was supported by the National Center for Research and Development of Poland, grant number Lider/60/0250/L-11/19/NCBR/2020.

References

[1] J. F. Łątka, “Paper in architecture: Research by design, engineering and prototyping,” Architecture and the Built Environment, 2017, doi: 10.59490/abe.2017.19.1875.

[2] P. Shenoy, P. S. Aithal, “A study on history of paper and possible paper free world.” International Joutnal of Management IT and Engineering, vol. 6, no. 1, pp. 337–355.

[3] J. F. Łątka et al., “Properties of paper-based products as a building material in architecture – An interdisciplinary review,” Journal of Building Engineering, vol. 50, p. 104135, Jun. 2022, doi: 10.1016/j.jobe.2022.104135.

[4] L. C. Bank and T. D. Gerhardt, “Paperboard tubes in structural and construction engineering,” Nonconventional and Vernacular Construction Materials, pp. 453–480, 2016, doi: 10.1016/b978-0-08-100038-0.00016-0.

[5] C. Correa, “Designing with Paper Tubes,” Structural Engineering International, vol. 14, no. 4, pp. 277–281, Nov. 2004, doi: 10.2749/101686604777963496.

[6] J. Schönwälder, and J. G. Rots“Mechanical Behaviour of Cardboard in Construction,” Cardboard in Architecture, 2008, doi: 10.3233/978-1-58603-820-5-131.

[7] L. C. Bank, T. D. Gerhardt, and J. H. Gordis, “Dynamic Mechanical Properties of Spirally Wound Paper Tubes,” Journal of Vibration and Acoustics, vol. 111, no. 4, pp. 489–490, Oct. 1989, doi: 10.1115/1.3269888.

[8] L. C. Bank, E. Cofie, and T. D. Gerhardt, “A New Test Method for the Determination of the Flexural Modulus of Spirally Wound Paper Tubes,” Journal of Engineering Materials and Technology, vol. 114, no. 1, pp. 84–89, Jan. 1992, doi: 10.1115/1.2904146.

[9] EN 1991:2004 – Eurocode 1: Actions on Structures. European Committee for Standardization (CEN)

[10] EN 1990:2002 – Eurocode 0: Basis of Structural Design. European Committee for Standardization (CEN)

[11] EN 1995:2004 – Eurocode 5: Design of Timber Structures. European Committee for Standardization (CEN)