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Modular Building Using Rammed Earth

Gabriela T. Ciurileanu (Cioca)[*1], Ildiko Bucur Horvath[2]

[1,2] *Technical University of Cluj-Napoca, Faculty of Civil Engineering. 15 C Daicoviciu Str., 400020, Cluj-Napoca, Romania*

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Abstract

Modular structures and prefabricated elements have revolutionized the building system by providing a fast and economic construction, due to serialization. Well known modular elements are the prefabricated multilayer panels, which are commonly used for exterior house walls. Each layer of the panel is designed to solve one of the important characteristics of an external wall, for example: compression strength, thermal insulation or waterproofing. In this article, a box with two compartments is proposed as a prefabricated module. In each compartment, a different material is compressed: earth and straw. The rammed earth has a structural role and the compression strength is tested in the Technical University of Cluj-Napoca Laboratory. The straws have the role of insulating the wall because of their low thermal conductivity. The wooden box in which the materials are compressed is designed as a modular element that can be built similar to a brick wall. This paper proposes the application of modular building principles, by using natural materials as wood, earth and straw in a building system that offers an ecological and economical alternative for building with industrial prefabricated modules.

Rezumat

Structurile modulare şi elementele prefabricate au revoluţionat sistemul constructiv oferind rapiditate la punerea în operă şi costuri reduse datorate serialităţii. Binecunoscutele elemente modulare sunt panourile prefabricate de tip multistrat, care sunt utilizate în mod frecvent ca pereţi exteriori ai locuinţelor. Fiecare strat al unui panou este destinat să rezolve una dintre exigenţele la care este supus peretele respectiv, de exemplu: rezistenţa la compresiune, izolare termică sau hidrofugă. În acest articol, o cutie cu două compartimente este propusă ca modul prefabricat. În fiecare compartiment este comprimat un material diferit: pământ şi paie. Pământul comprimat utilizat va asigura factorul portant, rezistenţa la compresiune fiind testată în laboratorul Universităţii Tehnice din Cluj Napoca. Paiele vor asigura izolarea termică a peretelui, datorită conductivităţii lor termice scăzute. Cutia de lemn în care materialele sunt comprimate este gândită ca un element modular, care se clădeşte asemeni cărămizilor. Această lucrare propune aplicarea principiilor construcţiilor modulare, folosind materiale naturale precum lemnul, pământul şi paiele în cadrul unui sitem constructiv ce oferă o alternativă ecologică şi economică de construire cu module prefabricate.

Keywords: rammed earth, straw, module, prefabricate, thermal insulation, compressive strength

[*] Corresponding author: Gabriela Teodora Ciurileanu (Cioca) Tel.: 0741930521
E-mail address: atelier_cadru@yahoo.com

1. Introduction

A prefabricated element is an industrial product in an intermediary phase of processing. A construction element, fabricated in advance in a factory, in order to be mounted and assembled along with other elements on the construction site [1]. The prefabricated element industry is a relatively new branch that appeared due to the sudden increase in the number of buildings in the twentieth century. This type of constructing system came as a result to the need of high quality in fast building projects, were easy manipulation of these elements led to new possibilities in architecture. The most common elements were prefabricated reinforced concrete. They are produced in special factories and brought to the building site where they are assembled.
One of these prefabricated solutions is the sandwich panel, brought on Romanian construction market in 1993. Depending on the internal layers, the panels are used for different types of buildings, from houses to farms and factories. This type of multilayer external wall usually contains external and internal wood cladding and mineral wool core insulation. The house has a timber or metallic structure.
In nowadays, there is a return to the basic building techniques and natural materials, especially in the more developed countries. For example, in SUA, Australia, China, New Zeeland, but also in Europe, in UK, France, Spain, Austria and other countries, the ecological buildings are more and more requested by the owners. All the new books, papers and news are announcing about new ideas developed in this area to encourage the common people to turn to nature. The basic building technique – the "do-it-yourself" technique – has been reestablished and the self sustained buildings are becoming more and more common. All these changes come as a result of the increasing global warming that determines us to preserve energy in any way possible.
In the Fig. 1 are presented the most common house building materials and their embodied energy [2]. As shown in the graphic, the lowest embodied energy is that of rammed earth. The embodied energy (carbon) of a building material includes all the energy consumed over its life cycle, all the carbon released, which includes extraction, manufacturing and transportation.

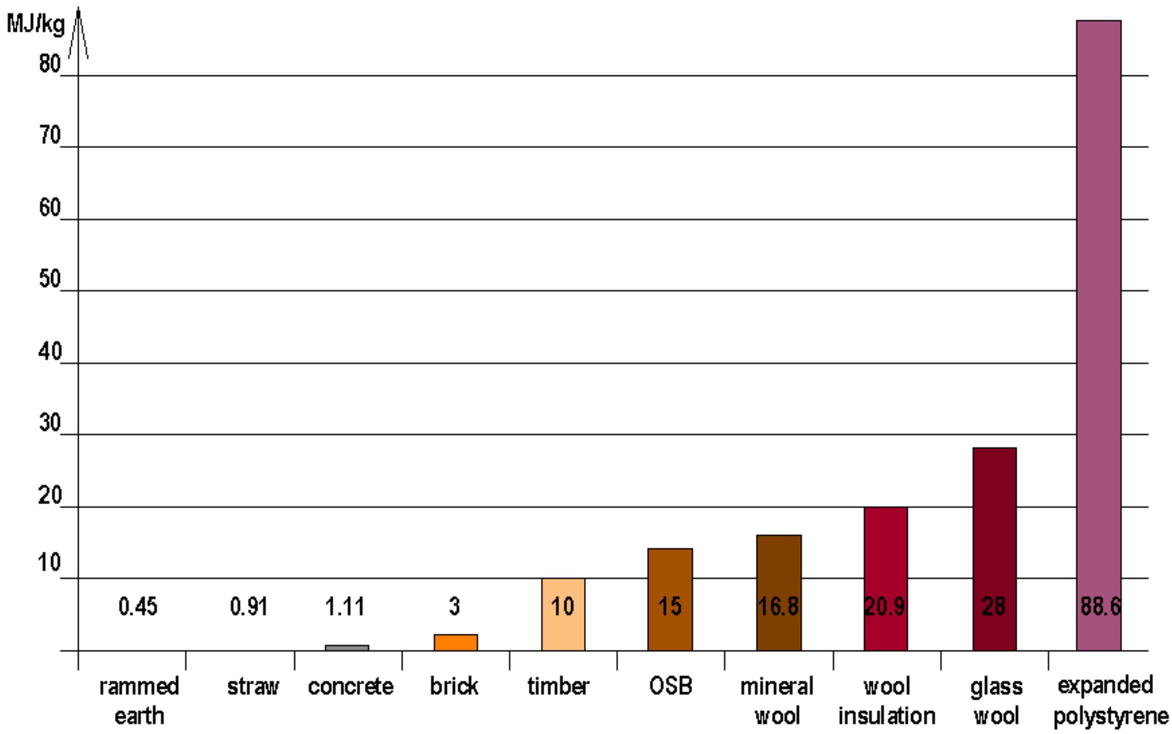

Figure 1. Embodied energy of common building materials

The traditional methods of building with earth have been adapted to contemporary techniques in order to provide modern, comfortable, insulated new buildings. Many countries developed standards that enable earth construction. The most accurate earth building standards and the first ones in the world to be exposed so clear and comprehensive are:
NZS 4297:1998 Engineering Design of Earth Buildings
NZS 4298:1998 Materials & Workmanship for Earth Buildings
NZS 4299:1998 Earth Buildings not Requiring specific Designs [3].
In Romania, traditional buildings are an important factor of our ancestral heritage. Natural materials as wood, earth, adobe, straws, cane, reed, were used as building materials for traditional buildings even from the Neolithic period (4200 – 3500 b.c.)[4]. Earth was manly used for building traditional vernacular houses in the south, or in other areas where wood was difficult to find.

2. Rammed earth as a building material

Today, earth is mainly viewed as a building material for the poor, especially in our country where these techniques are immediately related with the old houses of our great-grandparents. Anyone who wants to build a house, now, would rather use building materials commonly available in stores. Although earth is an atypical building material, it has many attributes that makes it stand out from other industrial produced building materials.
The main quality is the **ecological** and **economical** factor. It has a low embodied energy, and, as it is **available everywhere**, it is easy to build with especially for a “do-it-yourself” building. After the building is being abandoned, the material returns to its original location, so it is reusable and doesn’t leave construction waste.
Interior **air quality** of the house cannot be compared to one from a house built with common materials such as concrete. Earth balances air humidity by absorbing the humidity inside the house and creating equilibrium with the air outside. In this way, it maintains an almost constant air humidity of 50% for an entire year [5] and an air freshness that doesn’t need an air conditioning system.
Even it has a high thermal conductivity [5], rammed earth has a **high thermal mass**, so it can store heat captured during the day and release it in the house during the night after eight hours [5]. This quality is due to its **high density** 2000 – 1800 kg/m^3.
Depending on the soil mixture, rammed earth can have a **compressive strength** that allows it to form a structural wall. Even if a timber structure is needed due to a lower earth density, **earth preserves timber**, so they can work together creating a structural wall.
It is also a very good **fire resistant**. Many chimneys, stoves, fireplaces are made from rammed earth. Instead of damaging it, the fire hardens the earth.

3. Experimental test on rammed earth samples

In order to use rammed earth to build a house, earth from the site is first collected. Samples from a site in Romania, near Cluj Napoca, were taken. The geotechnical study reveals that it is a clayey soil. The soil contains 33% clay, 42% dust and 25% sand. Clayey soils absorb more water [6] and can generate cracks when drying.
According to other studies [6], in order to increase the compressive strength of rammed earth, the used soil should not be too clayey. An ideal soil contains 15-16% clay. That is why in the recipes proposed for study, the quantity of sand is increased in order to diminish the clay percentage.
In Table 1 are proposed and described four earth recipes. Increased percentages of sand are added to the same amount of earth and for the final samples, Portland Cement 42.5N is also added.

Table 1**:** The recipes proposed for rammed earth

Name of recipe	**Earth (kg)**	**Sand (kg)**	**Portland Cement (kg)**	**Water (l)**
1.Natural earth	9	-	-	8% from the amount of earth 0.72l
2.Earth and 25% sand	9	25% from the amount of earth 2.25 kg	-	8% from the amount of earth 0.72l
3.Earth, 50% sand and 5% Portland Cement 42.5N	9	50% from the amount of earth 4.50 kg	5% from the amount of earth 0.45 kg	10% from the amount of earth 0.9l
4.Earth, 70% sand and 8% Portland Cement 42.5N	9	70% from the amount of earth 6.30 kg	8% from the amount of earth 0.72kg	10% from the amount of earth 0.9l

The three samples for each recipe are each rammed into 10 cm^3 metal molds and extracted from the mold the next day, as shown in Fig. 2.

Figure 2. Earth sample after extrusion from the mold, after 28 days of curing and after being tested for compression strength

The samples are kept 28 days for curing in an indoor environment. Then, the samples are tested for compressive strength in the Technical University of Cluj-Napoca Laboratory and the results are presented in Table 2.

Table 2: The compressive strength results

Name of the sample	**Dimensions (mm)**	**Force applied (kN)**	**Compressive strength (N/mm^2)**
1.Natural earth cube	0.1x0.1x0.1	45.5	2.122
2.Earth and 25% sand cube	0.1x0.1x0.1	30.0	1.370
3.Earth, 50% sand and 5% Portland Cement cube	0.1x0.1x0.1	55.1	2.449
4.Earth, 70% sand and 8% Portland Cement cube	0.1x0.1x0.1	42.2	1.870

As seen in Table 2, the best results came from the simple earth cube (2.122 N/mm^2) and from the one with the mixture of 5% Portland Cement, earth, sand and water (2.449 N/mm^2).
The results are compared to the foreign standard New Mexico Earthen Building Materials Code,

that requires a minimum 2 N/mm² compressive strength for a one or two-level house [7].
So, according to this code, the earth from the site can be used for building a one or two-level house. It can be used in its raw form or it can be mixed with 5% Portland Cement as shown above.

4. Building principles for natural materials

Building with rammed earth is similar to building with concrete. A formwork has to be set on place and the mixture is usually prepared with a mechanical mixer. Usually, the formwork needs to be bought or rented and for its installation and removal, more than one person is required. Sometimes, a qualified personal has to install the formwork. After the formwork is set, the earth mixture is poured into 20 cm layers and rammed until it becomes 50% of its original height. When the formwork is removed, pieces of earth that have not been rammed properly can separate from the wall. Also, if it's not finished properly, in time, dust may come off the wall's surface.
Straw bale can create a structural wall for a one-level house, if the straws are very well compressed inside the bale. Usually new straw bale houses have a wooden or metal structure. Old brick houses can be insulated using straw bale; in this case the brick wall is structural. The issue when building with straw is that they need to be well compressed, linked together, and they have to be formed into bales in order to be able to stack them one over the other. When insulating a brick, concrete, earth wall, the straw bales attached need to have a separate wooden or metal structure that can hold them together and connect them to the structural wall.

4. Prefabricated wooden modules

In order to be able to build using both rammed earth and straw in the same module, the idea of a prefabricated element that would eliminate the problem of the formwork and the structure that holds the bales, is studied. In this way, the formwork is lost and becomes part of the building, being transformed into a structural part of the wall that will also separate de materials and finish the wall towards the interior. Also, the necessity to purchase the straw formed into bales and to build the separate structure that holds the bales near to the wall is not needed anymore. The module proposed is a box with no bottom that can be made of different type of materials: wooden boards, OSB, perforated recycled plastic or metal sheet, etc. In the presented article, the module is made of wooden boards; material chosen because is natural and the least expensive.

4.1 Module's dimensions

In Fig. 3 is presented the wooden module. It has two compartments: one for rammed earth and one for any insulating material, in this case, straw. Minimum dimension for a rammed earth structural wall is 30 cm [5]. That is why the rammed earth compartment needs to be 30 cm wide or more. The width of the second compartment is generated by the calculated heat transfer coefficient, U, for the exterior wall. The length of the box, 110 cm, is generated by the capacity of the wooden boards to resist the pressure of the rammed earth. It is also double the width of the box, which is 55 cm. In this way, the module can create walls that have a length multiple of 55 cm. The height of the box is half the standard window parapet, 90 cm, so, two modules are necessary before creating a window opening. The boards of the module are attached to six vertical slats, 4x4x65 cm, that exceed the height of the box in order to permit a connection between two different rows of boxes. There are two versions presented in Fig. 3. In the first version, the slats are exceeding the dimension of the box in two different directions. In this way, a box connects with the upper and the lower row in the same time. In this case, two rows of boxes are set before the materials are put inside the first row. In the second version, the slats are set in the same direction, so any row can connect to the one above. In this case, one can set the first row of boxes, then put the materials inside, then set the second row.

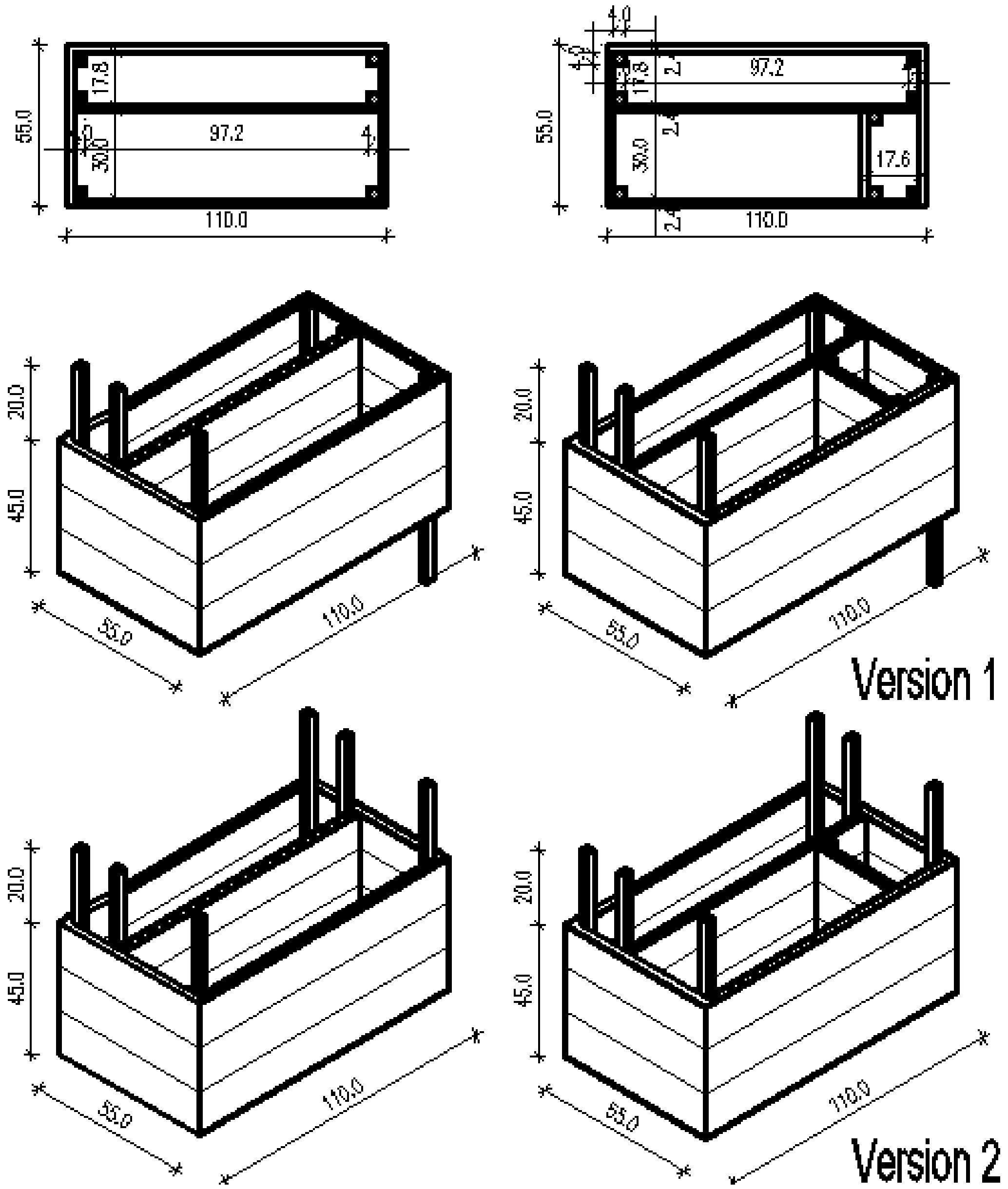

Figure 3. Wooden box module, example for field and corner

4.2 Building with the modules

When starting a house building, the first step is the foundation. It has to be dimensioned according to the wooden modules. After the cement is poured in the foundation's formwork, wooden boards are fixed on the surface of the foundation on the hydro isolation, on the entire perimeter where a wall has to be built. Then, a waterproof paint – cold bitumen paint - is brushed over it. The first row of boxes is set, starting from a corner. The boxes are nailed together and also on the wooden board connected to the foundation. In each box a layer of 5 cm gravel is set on the bottom, which would prevent water to reach the straws or the earth.

In the case of the first version of modules, after the first row of boxes is set, one needs to set another row on top of the first one and then put the materials. In the second version, after the first row of boxes is set, the earth mixture can be poured in, over the gravel, and rammed at 50% its original height. The straws are set in their compartment and pressed, in order to achieve a density close to 300 g/cm³. Fig. 4 presents three-dimensional versions of the modules and an example of how they are built into a modular wall.

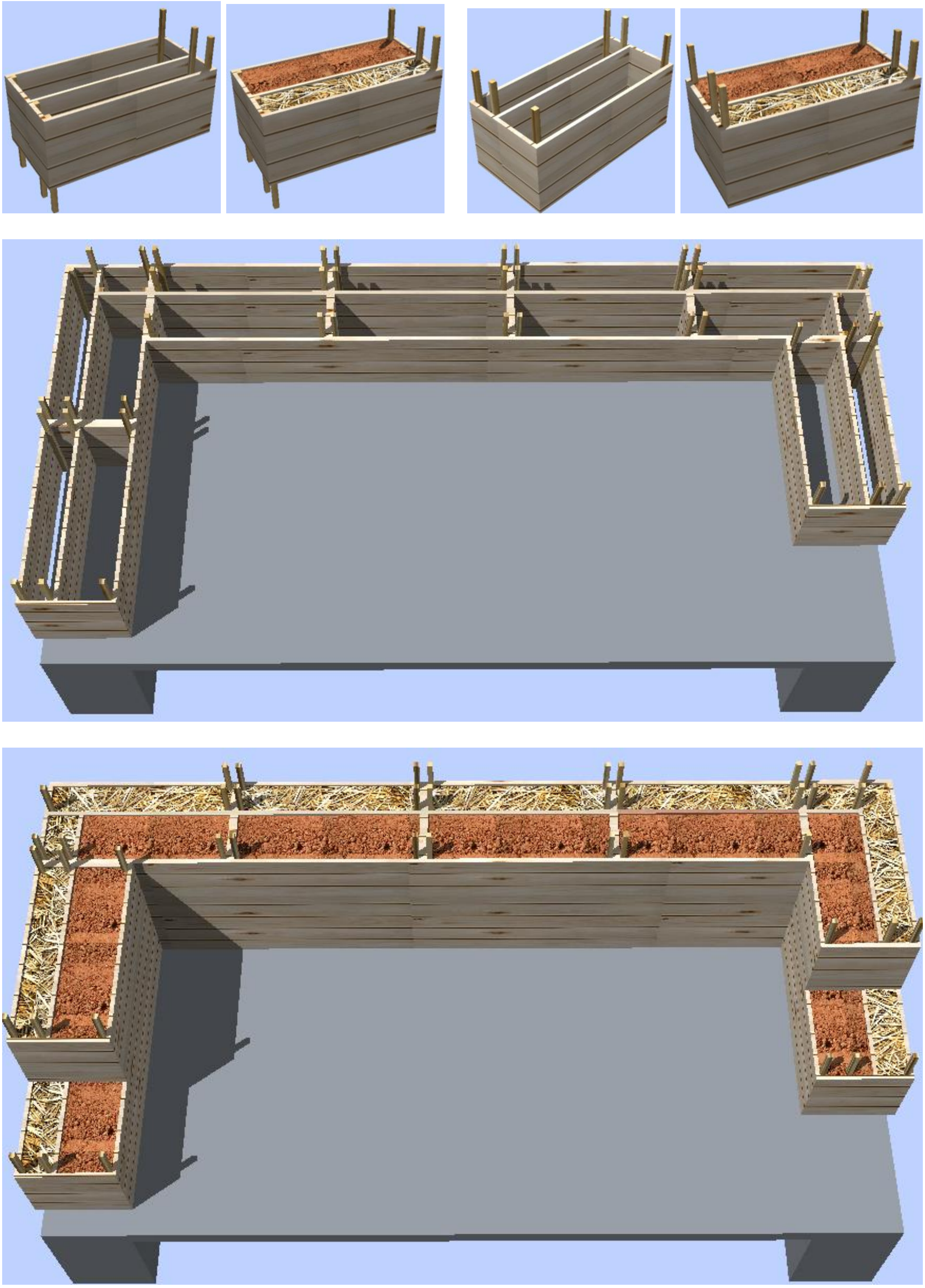

Figure 4. Example of wall built using the box-module

4.2 Thermal insulation and costs of the wall

Table 3: Thermal resistance and price for sqm of wall

Materials	**λ (W/mK)**	**d (m)**	**Rsj (W/ m²K)**	**Price / m² wall (lei)**
1.Resinous wood paneling	0.17	0.024	0.14	6.20
2.Rammed earth	1.5 [5]	0.30	0.20	0
3. Resinous wood paneling	0.17	0.024	0.14	6.20
4.Straw bale	0.061 [3]	0.178	2.91	2.6
5. Resinous wood paneling	0.17	0.024	0.14	6.20
6. Resinous wood paneling at the end of the box + vertical slats				8.4
TOTAL		**0.547**	**3.53**	**30**

Specific unidirectional thermal resistance of the outer wall is:
(1) $R = Rsi + \Sigma\, Rsj + Rse = 0.125 + 3.53 + 0.042 = 3.697$ m²K/W
Minimum thermal resistance according to Romanian standard C 107 – 2005 (Annex 3) for new residential building, is: $R_{min} = 1.40$ m²K/W [9]
(2) $R > R_{min}$
(3) 3.697 m²K/W > 1.40 m²K/W
Heat transfer coefficient U for the exterior wall is:
(4) $U = 1/R = 1/3.697 = 0.27$ W/m²K
The maximum heat transfer coefficient, U, for exterior walls, on type „b" buildings (which includes residential buildings) is 0.53 W/ m²K according to Annex no.10.17 [10].
(5) $U < U_{max}$
(6) 0.27 W/ m²K < 0.53 W/ m²K
According to Eq. (3) and (6), the exterior wall proposed is insulated enough to fit the Romanian standards. If desired, the second compartment of the box can be filled with other type of insulating materials as natural wool, mineral wool, recycled textile waste, recycled PET bottles, recycled cellulose, etc. The new heat transfer coefficient, U, is then calculated accordingly. After the boxes are set, the exterior side of the wall can be plastered using a 3 cm earthen plaster on cane or metal wire, or can be covered with different type of panels, metal sheets, wooden boards that are fixed on vertical wooden slats. In this way, ventilated air can flow underneath and protect additional rain water and humidity to reach the materials from the wall. It also permits air to circulate and ventilate the wall, creating equilibrium between air inside and outside the house. The ventilated air cavity eliminates any possible humidity accumulated inside the wall.
The material costs for an m² of wall, as shown in Table 3, are calculated according to Romanian materials market, on March 2012. If the boxes can be made by the owner, there is no need for paid manual labor. When compared to a typical house building, with usual materials, the price is three times lower. For example, only the materials for a brick house insulated with 10 cm polystyrene cost around 110 lei/m² and for a wooden house with sandwich panel exterior walls, the cost is around 90 lei/m². When adding the manual labor involved, the price becomes double or higher most of the time.

7. Conclusions

The article proposes the idea of building natural, using a prefabricated system.
The study presents several conclusions:

- local earth from the site can be used for one or two-level house building
- the compressive strength obtained for a 10 cm^3 rammed earth cube in Technical University of Cluj-Napoca Laboratory, is 2.122 N/mm^2, and is higher than minimum compressive strength required by known external codes as New Mexico Building Code
- a modular element is proposed – a wooden box that has two compartments: one for the material offering the resistance of the wall (rammed earth) and one for the material with insulating properties (straw)
- the modules are designed to be able to form a rigid structural wall
- this method enables the use of non professional manual labor.
- the heat transfer coefficient obtained for the exterior wall, U, is higher than the minimum value accepted by Romanian standards.
- the cost of the modular wall is two or three times lower than the cost of a house build with common materials.

In a time governed by the economic crisis, the building sector is stagnant. Alternative solutions need to be discovered and applied because, according to Romanian referendum from 2011, there are 165 000 people living in social shelters or without a home. The use of local natural materials becomes a solution at hand for any person who needs a home. The article presents a new solution of making the building process faster, easier and accessible to untrained people. Also, one can incorporate along with earth, any type of insulating material that is at hand when building with this type of modular boxes. This paper proposes applying the modular building principles, while using natural materials as wood, rammed earth and straw as building materials.

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