Journal of Civil Engineering and Architecture 16 (2022) 497-512
doi: 10.17265/1934-7359/2022.10.003

Sturdy, Durable, Fast-To-Build, and Low-Cost Ferrocement Houses

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Abstract: This paper presents the experience in building low-cost houses in ferrocement technology, arched cross-section with on-site construction, using skeletal method combined with steel hollow structural sections. The author wanted to develop a simpler, faster and more cost-effective system of the construction of smaller buildings, retaining their stability and durability, energy-efficiency and resistance to earthquakes and storm winds at the same time. The goal was to enable non-professionals to build houses in quick and simple way using standard, easily accessible materials and tools. Houses such as described in this paper were built in DR Congo (Democratic Republic of the Congo) and have proven to be, fast-to-build, safe, durable and serviceable with practically no maintenance required. In 2016, 15 such houses were built in less than four months. The author has promoted the solution for construction of such houses in continent climate conditions too, using stronger frame and much better thermal insulation, without thermal bridges.

Key words: Ferrocement, low-cost houses, energy-efficiency, resistance to earthquakes.

1. Introduction

The author's first experiences in the application of ferrocement technology, dates back to 1981. He constructed his first ferrocement dome using the Skeletal Armature Method described Naaman [1, 3, 4, 5, 6].

Later, the author developed the MC System of sustainable construction [2], which includes the use of prefabricated, flat, thermo-insulated, three-layer ferrocement elements for the rapid construction of permanent semi-cylindrical polygonal structures, with a range of up to 33 m in width (so far), lengths as needed, as intended for different purposes.

One leading application of the MC system with significant cost benefits were found in the construction of sport's halls and covered swimming pools.

However, using the MC System in the construction of individual small residential buildings or housing units, issues with cost-effectiveness become clear, namely: investments in the production and transportation of prefabricated ferrocement elements, and on-site scaffolding and erection crane for their installation are necessary.

For this reason, the author decided to develop a simpler, faster and more cost-effective system of construction for smaller buildings.

The main goals were:

(1) Provide sturdy, durable, fast-to-build, and low-cost facilities.

(2) Achieve high level of resistance to earthquakes and stormy winds.

(3) Realize satisfactory thermal characteristics of the facility.

(4) Realize rapid construction with a local workforce.

(5) Enable to use only standard tools on construction site.

(6) Ensure the use of all necessary materials only in standard factory dimensions-waste minimization.

This paper describes the construction of sustainable houses using ferrocement technology.

Simplified procedures for the serial construction of row of low-cost, durable houses, thermally insulated, were explained. The paper gives a description of construction of open space housing and their folding

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Fig. 1 Houses in row.

Fig. 2 Serial construction.

up of structural, lightweight arched hollow steel sections, light reinforcing mesh and welded wire mesh (Figs. 1 and 2).

By fixing polystyrene boards on the inside of the structure, between arches, the formwork for the application of plaster is made, and at the same time thermal insulation layer is formed.

The procedure of forming a ferrocement shell provides stabile static system with the steel skeleton. In this way, a unique interior space of the object is formed. That space can be partitioned by a drywall or any other method according to habitants' requires. Complete interior space can be easily redesigned because the partition walls are not load-bearing walls.

Based on an extensive preliminary evaluation and a numerous of design iterations, the author selected a modified semi-cylindrical form as the optimal shape (Fig. 3).

The shape and dimensions of the house were chosen very carefully, all high-priced materials, steel profiles, reinforcing meshes, polystyrene boards, plaster boards are embedded in standard factory dimensions. In this way, the amount of waste from the materials used is reduced to a minimum.

Paper contains detailed review of construction procedure, material consumption and price analyses. During the year 2016, 15 such buildings were built in less than four months.

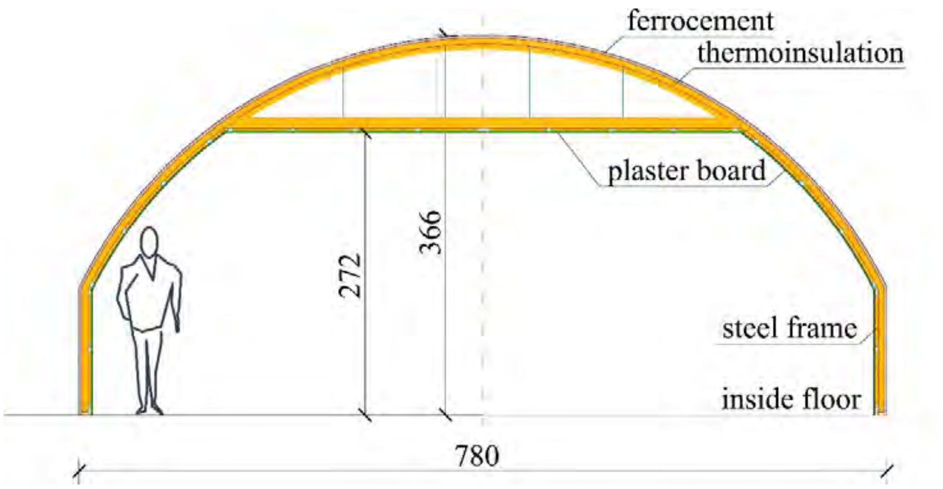

Fig. 3 Vertical cross section.

Fig. 4 Local workers.

Houses, especially quickly built by described technology are sturdy, durable, energy-efficient, resistant to earthquakes and strong winds. Fire cannot make structural damage and objects are handgun bulletproof, on site testing proved.

These houses were built in DR Congo (Democratic Republic of the Congo), with local workers (Fig. 4), so the thermal insulation of houses is adapting to tropics climate conditions there. The author has promoted the solution for construction of such houses in continent climate conditions too, using stronger frame and much better thermal insulation, without thermal bridges. Ferrocement construction is strengthened by ferrocement ribs from outside. Dimensions of ribs are calculated so that they can carry the weight of the soil layer above, which enable effective green roof.

In this way, houses provide a high level of energy efficiency, up to passive house level.

2. Methods and Materials

This construction system uses ferrocement technology using the Skeletal Armature Method described by Naaman [1].

The following steps describe the construction process.

2.1 Foundation

On the level and compact ground, a 7 cm thin reinforced concrete slab strengthened by ribs along its edges is poured (Fig. 4).

2.2 Putting Up of Steel Arches

Arched rib elements from already welded light steel rectangular profiles 60 × 30 × 2 mm, are placed vertically on the concrete foundation edges with 100 cm spacing in between (Fig. 6).

2.3 Welding Arches

To obtain a firm structure, horizontal steel armature rods are welded to the metal arches (Fig. 7).

2.4 Welding of Reinforcing Mesh

Reinforcing mesh was welded to the formed steel skeleton (Fig. 8).

2.5 Putting Up Galvanized Wire Mesh

After that, two layers square welded galvanized wire meshes are placed on outside of the welded reinforcing mesh (Fig. 9).

2.6 Installation Polystyrene Boards

Standardized polystyrene boards (100 × 50 cm) are placed on the inside of the structure between the arched steel profiles. Thin steel wire boards are fixed to the reinforcing mesh. The polystyrene boards have

Fig. 5 Foundation.

Fig. 6 Putting up of steel arches.

Fig. 7 Welding arches.

Fig. 8 Welding reinforcing mesh.

Fig. 9 Putting up galvanized wire mesh.

Fig. 10 Installation of polystyrene boards.

two roles: during the construction phase they act as support for placing the mortar, and during usage, they form a thermo-insulating layer (Fig. 10).

2.7 Plastering

Next, the cement mortar is plastered from the external sides of structural shell and front walls (Fig. 11).

2.8 Waterproofing

From outside a hydro-insulation layer is applied (Fig. 12).

2.9 Installation of Plasterboard Supports

From inside of the structure, standard galvanized profiles are mounted to later support plasterboards and ceilings (Figs. 13 and 14).

2.10 Installation of Plasterboard

Plasterboards are placed and thus the interior space is formed (Fig. 15).

Fig. 11 Plastering.

Fig. 12 **Waterproofing.**

Fig. 13 **Installation of plasterboards supports.**

Fig. 14 **Supports for roof plasterboards.**

Fig. 15 Installation of plasterboards.

Fig. 16 Partition walls.

2.11 Partition Walls

The interior space can be organized without any restriction since the partition walls are not load-bearing walls (Fig. 16).

2.12 Interior Details

Some examples of possible interior details and layout are shown in Fig. 17.

3. Results and Discussions

3.1 Cost Analysis

A detailed cost analysis (Table 1) was made for a house of 8 × 12 m (Fig. 18) including the finished interior as shown in Fig. 17.

3.2 Possibilities of Application

From an architectural design and layout perspective, several possibilities for applications have been considered and are illustrated in Figs. 19-23.

3.2.1 Residencial Objects (Fig. 19 and 23)

3.2.2 Schools (Fig. 20)

3.2.3 Hospitals (Fig. 21)

3.2.4 Military Storage (Fig. 22)

3.3 Solution for Continental Climatic Conditions

These houses were built in DR Congo, Africa, so the thermal insulation of houses is adapted to tropics

Fig. 17 Interior details.

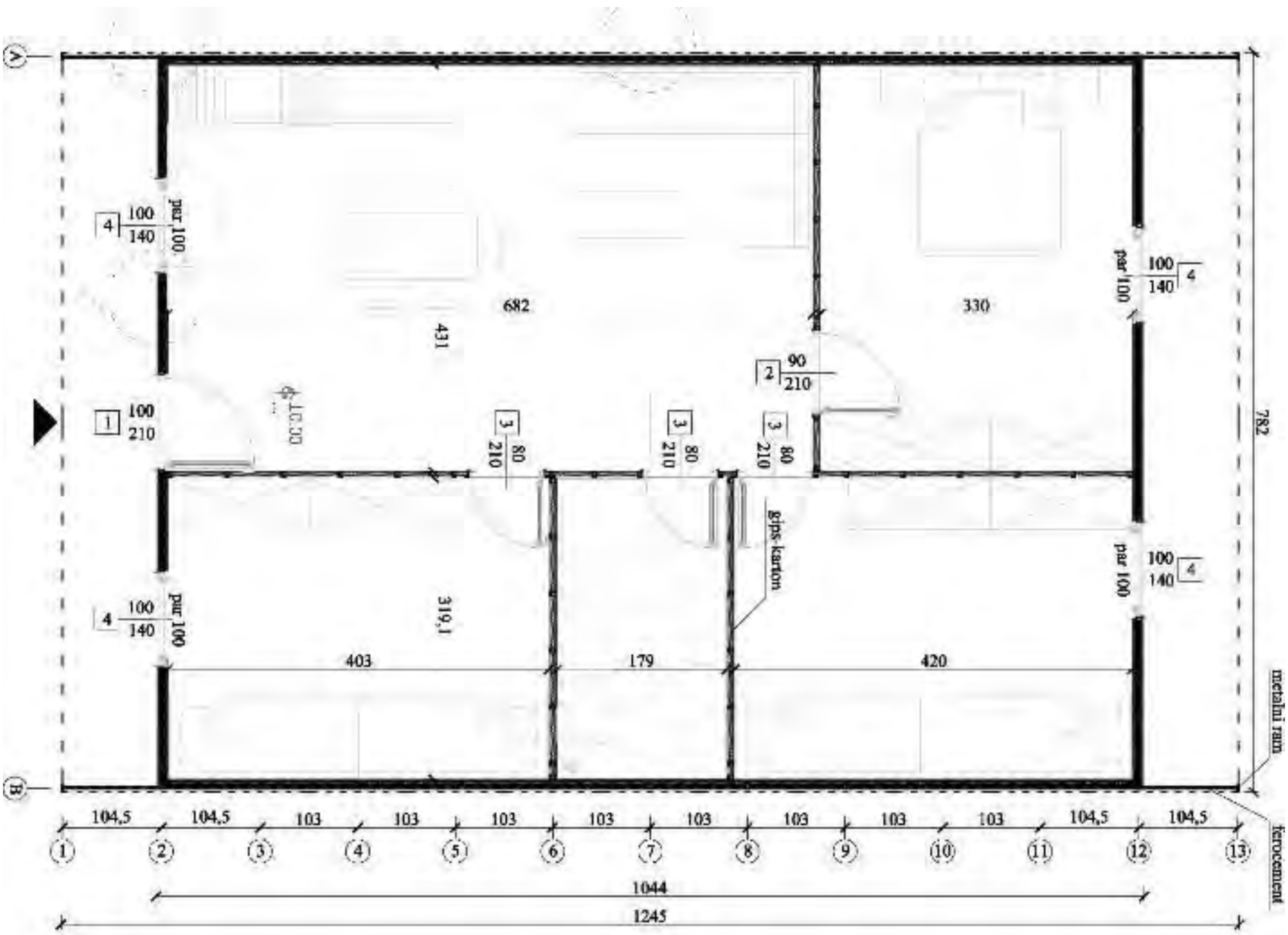

Fig. 18 House 8 × 12 m.

Table 1 Materials and prices.

	Description	Quantity	Price per unit	Total €
1	Concrete	12 m × 8 m × 0.08 m ≈ 8 m^3	65	520
2	Metal profiles	630 kg	0.7	441
3	Reinforcement bars	480 kg	0.6	288
4	Reinforcement mesh	520 kg	0.7	364
5	Wire mesh	370 m^2	1.5	525
6	Polystyrene	10 m^2	50	500
7	Mortar	6 m^3	80	480
8	Gypsum boards with accessories	280 m^2	4.5	1,260
9	Windows	4 pieces	90	360
10	Doors	5 pieces	130	650
11	Waterproofing	150 m^2	9	1,350
Total materials				6,738
12	Fees	180 man/day	20	3600
13	Electrical installations			320
14	Water and sewerage			280
15	Furnishing bathroom			560
All in total				11,498
per m^2				143

Fig. 19 Residential complex.

Fig. 20 Schools.

Fig. 21 Hospitals.

Fig. 22 Military ammunition storage.

Fig. 23 Villa Tanganjika, DR Congo.

climate conditions there. The author has developed a solution for the construction of such houses and for continental climate areas using stronger frame and much better thermal insulation, without thermal bridges. Ferrocement construction is strengthened by ferrocement ribs from outside, dimensions calculated to allow covering with soil aiming to realize an effective green roof. In this way, houses achieve a high level of energy efficiency, up to passive house level (Figs. 24-31).

3.4 Ferrocement Housing Project from Shelter to Home

Natural disasters (earthquakes, stormy winds...) result in great destruction and human casualties, for most of colapsed buildings.

Self-built small ferrocement structures enable, not only fast care of the homeless, but also full protection from future natural disasters.

Figs. 32 and 33 are an example of one such solution.

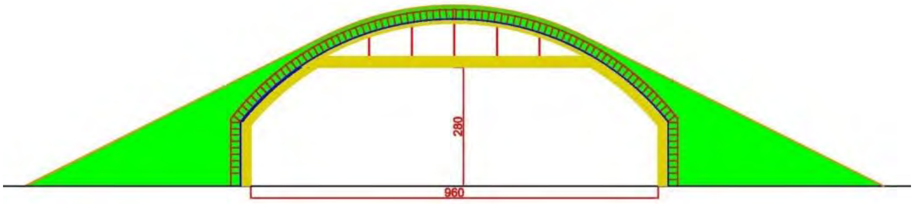

Fig. 24 Vertical cross section.

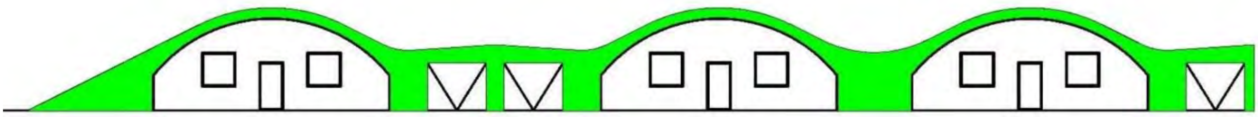

Fig. 25 **The houses in a row.**

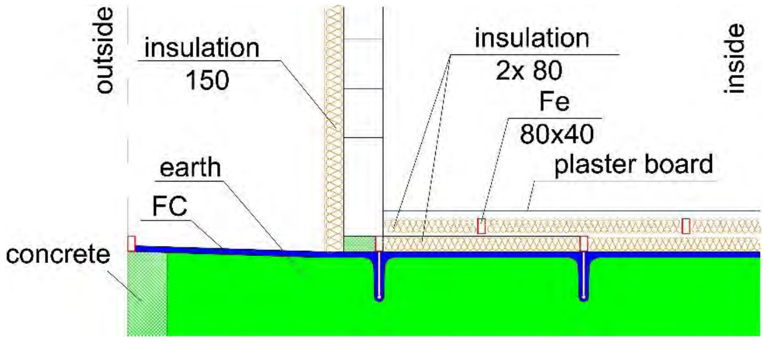

Fig. 26 **Horizontal cross section.**

Fig. 27 **Steel construction.**

Fig. 28 **Placement polystyrene boards.**

Fig. 29 A waterproofing.

Fig. 30 Covering with soil.

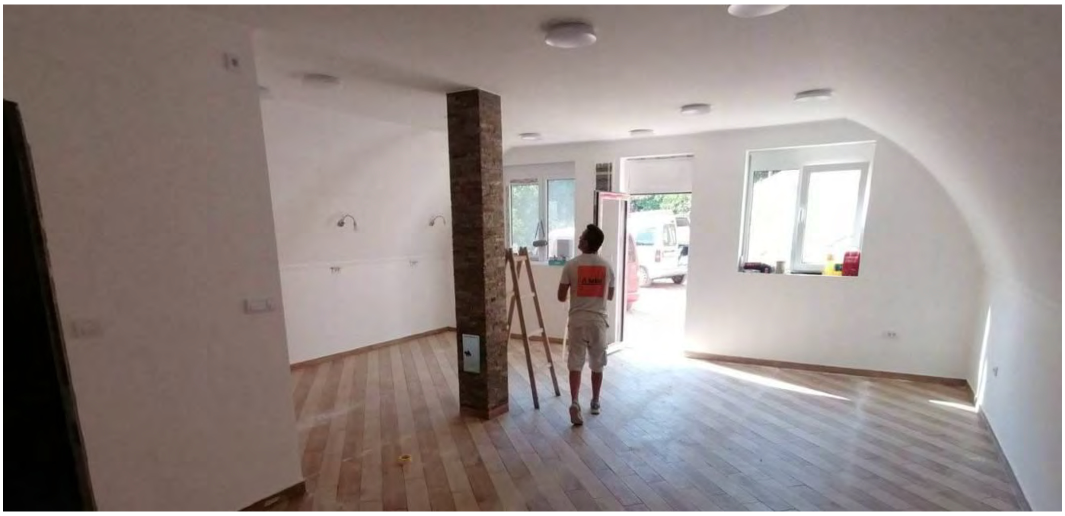

Fig. 31 Interior details.

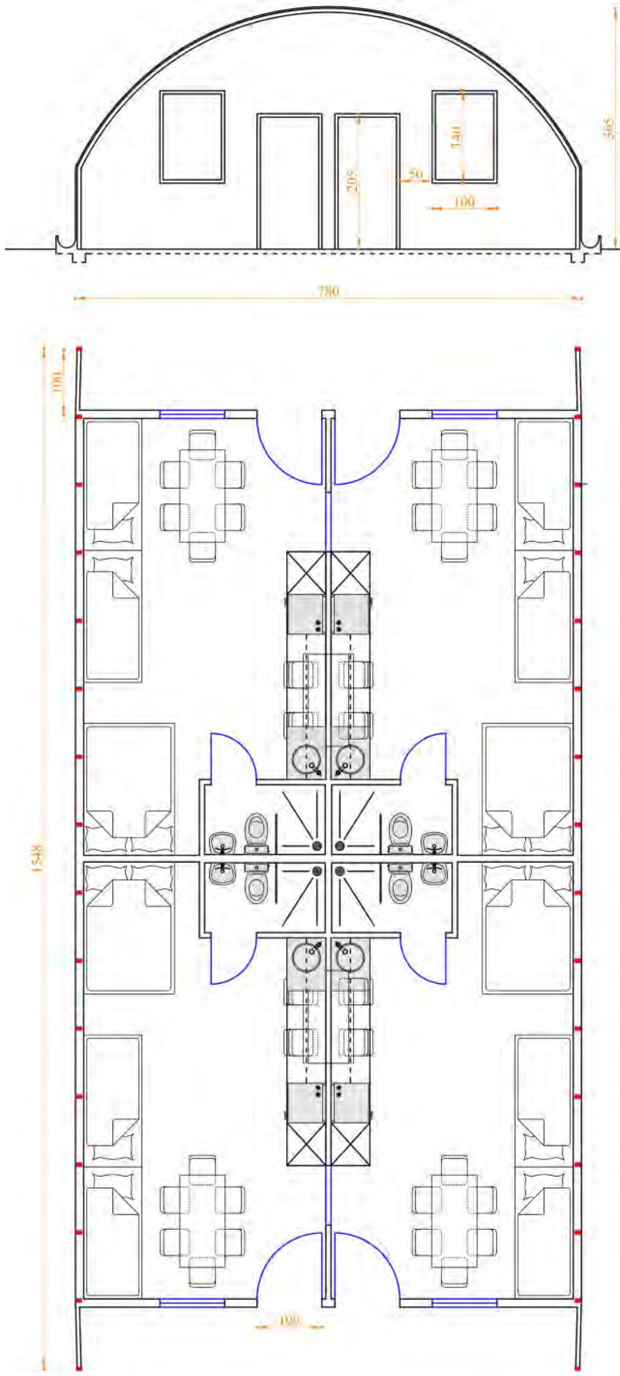

Fig. 32 The shelter ×4.

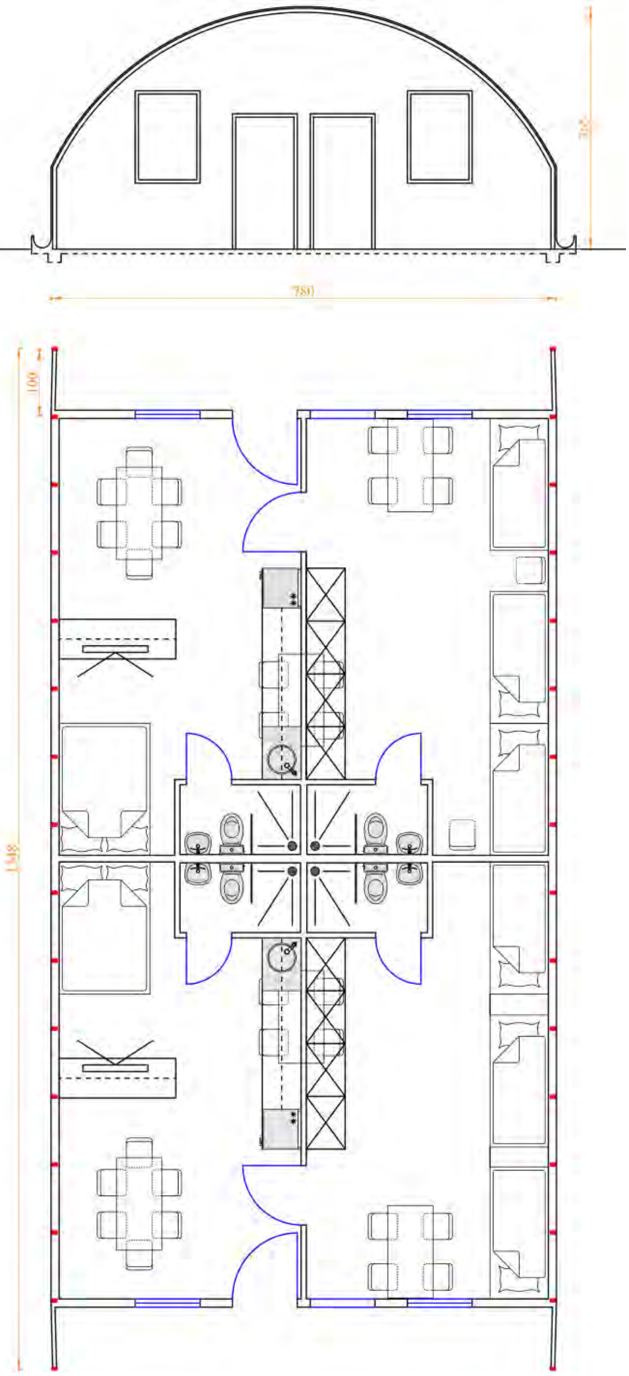

Fig. 33 Home ×2.

4. Conclusion

Sturdy, durable fast-to-build, and low-cost ferrocement houses can be built simply as individual self-built or serially as entire settlements. In this way it is possible to quickly take care of the homeless and their complete protection from natural disasters. Since in this solution no partion wall is load-bearing, reorganized very quickly and easily in accordance with the new needs.

By installing an appropriate thermal insulation layer, without thermal bridge, and especially by filling the house with soil, a high level of energy efficiency is achived, up to the level of pasive house.

Fig. 34 The first ferrocement object 41 years old.

Since today about 40% of the total energy consumption in the world is spent on buildings, this gives this solution great advantages compared to existing solutions.

This solution enables fast construction, safety, durability and functionality, practicaly without maintance costs.

Author's first dome built in ferrocement technology forty years ago, has a leyer of lichen formed on the outside and same color on the inside from the moment of construction. The ferrocement structure of the shell is completely preserved undamaged (Fig. 34).

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