Tubular House - Form Follows Technology, Concrete Shell Structure with Inner Thermal Insulation

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Abstract. The aim of this paper is the theoretical analysis of the possibilities and limitations of using an unconventional technology and the original architectural form stemming from it – the building with external construction and internal insulation. In Central European climatic conditions, the traditional solution for the walls of heated buildings relies on using external thermal insulation. This stems from building physics: it prevents interstitial condensation of water vapour in the wall. Internal insulation is used exceptionally. This is done e.g. in historical buildings undergoing thermal modernization (due to the impossibility of interfering with facade). In such cases, a thermal insulation layer is used on the internal wall surface, along with an additional layer of vapour barrier. The concept of building concerns the intentional usage of an internal insulation. In this case, the construction is a tight external reinforced concrete shell. The architectural form of such building is strongly interrelated with the technology, which was used to build it. The paper presents the essence of this concept in descriptive and drawing form. The basic elements of such building are described (the external construction, the internal insulation and ventilation). As a case study, authors present a project of a residential building along with the description of the applied materials and installation solutions, and the results obtained from thermal, humidity and energetic calculations. The discussion presents the advantages and disadvantages of the proposed concept. The basic advantage of this solution is potentially low building cost. This stems from minimizing the ground works, the simplicity of the joints and the outer finish, as well as from the possibility of prefabrication of the elements. The continuity of the thermal insulation allows to reduce the amount of thermal bridges. The applied technology and form are applicable most of all for small buildings, due to limited possibilities of lighting the interior. The disadvantage of this technology is low heat accumulation of walls. A building in the proposed technology requires constant, forced ventilation. Further theoretical and practical research towards applying this concept would be necessary.

1. Introduction

Today, the adoption of the principles of sustainable development necessitates searching for architectural solutions that are not only environment-friendly and socially acceptable, but also economically viable. This concerns in particular the house-building industry, due to its large scale. Dwellings are expected to be provided for everyone, thus requiring properly low costs of construction and operation of buildings. The challenge for the designers is to ensure that the living standard of the dwellers or environmental quality are not sacrificed for the sake of cost reduction. One of the methods for achieving this is to search for innovative solutions [1]. Economical management of resources...
roused interest in the available technologies, including prefabrication of buildings [2]. At the same time, a growing need for individualisation of houses may be observed [3]. Searching for innovative and economically viable solutions, the authors of this present study have researched the application of an unconventional construction technology: an outer concrete structure with inner thermal insulation. The purpose of the study is to analyse the theoretical capabilities and limitations of this technology. In this case, the architectural form of the building is a result of the technology, thus those elements are analysed jointly based upon an original conceptual design.

2. Essence of the design

In the Central European conditions of the humid continental climate, for example in Poland, the average annual temperature in winter falls below 0°C (32°F). This necessitates the use of space heating systems in housing buildings. The heating season lasts approximately half a year. The traditional and commonly used construction technologies are based upon the use of masonry in outer walls with external thermal insulation. This solution results from the building physics – it allows to avoid the adverse effect of water vapour condensation in the composite wall of the building. In case of existing buildings subject to thermal upgrading, e.g. architectural monuments, sometimes, interference in the exterior wall finishing is not an option. In such cases, thermal insulation is unusually applied on the inner side of the masonry wall. This may result in water vapour condensation in the composite wall. In order to prevent this, an additional vapour control layer is usually applied from the inside [4]. The inner wall thermal insulation technology is seldom used in construction of new buildings; one example of such a solution are Mabudo prefabricated walls [5].

The design proposed is based upon deliberate use of the outer supporting wall with inner thermal insulation technology for new buildings. It is unique in its use of a single technology for the floor, walls and roof, and in continuity of those elements (figure 1). This is made possible by giving the
Building the form of a closed section. An impenetrable reinforced concrete shell, the shape of which is tube-based (hence the name ‘tubular house’), constitutes the structure here: natural lighting and entryways have only been provided for on two sides (gable elevations). Shaping the building in such manner allows for eliminating the foundation-related earthworks and traditional roofwork, and for limiting the external finishes. This reduces the construction costs. The external structure allows for moving the building. The architectural form of such building is largely dependent upon the technology used for its construction (form follows technology). The basic forms (figure 2) may be potentially blocked, connected and complicated.

![Figure 2. Possible basic forms of a ‘tubular house’](image)

3. Analysis of the main elements of the building
The main elements of the building are the outer structure and the inner insulation. In case of the structure, the material used, construction technology and aesthetics must be analysed (the structure is not subject to cladding here). The inner insulation involves analysis of the building physics and the need to provide proper thermal, moisture and service conditions (of the ventilation).

The use of the structure as the outer layer necessitates the use of a material that is resistant to weather conditions, in particular to water. High water impermeability, combined with the ability to easily shape the tube limits the selection of construction materials. It is possible to use glued-laminated timber, plastic or steel. However, from the economical perspective, waterproof reinforced concrete appears to be the most suitable. In case of reinforced concrete (which is a porous material), water impermeability is arbitrary. In other words, it may not be assumed that water would never be able to permeate through that baffle. However, if the time needed for this to occur is longer than the estimated life span of the building, we may regard it as impermeable. Concrete of the proper water impermeability level (from W2 to W12, according to Polish standards) may be used, as necessary. Waterproof concrete has impermeability of W8 or higher [6]. Proper coating, impregnation or hydrophobic impregnation may be used for additional surface treatment of the concrete.

Prefabrication or in situ construction (i.e. the so-called pouring on site) is used as the technology for making reinforced concrete structures. Prefabrication allows for more precise construction, due to the mixture having matured in controlled conditions. By observing the technological regime, it is possible to create waterproof reinforced concrete elements which are at least 15cm (5.9in) thick. In order to achieve such water impermeability for elements poured on site, they must be at least 24cm (9.4in) thick and made of at least class B30/W8 concrete (according to Polish standards). Thickness of the structure also depends upon its span. For elements made in situ, the span may be selected from a broader range of options than in the case of precast products. The span of a prefabricated structure is limited by the transport capabilities. In case of land transport, the standards concerning the maximum dimensions of a multi-unit truck are similar across Europe. Those are: length 16.5m (54ft), width 2.55m (8.4ft), height 4m (13ft) [7]. Oversized elements may also be transported. However, that is more complicated and costly. The building dimensions resulting from the basic transport limitations
are too small to have a significant impact on the load bearing capacity of the structural components. Therefore, such building will have a simple structural system, with no significant bracing, stiffening, or strutting. To summarise, section views of the structural components depend upon the span, construction technology (prefabrication/in situ) and water impermeability.

The outer structure is not concealed or clad. It has an effect on the reception of the building and on its architectural expression. Therefore, it is recommended to make the structure from architectural concrete. The external characteristics of this material may be adjusted. The colour of architectural concrete is influenced by: (1) cement colour – from white to grey; (2) colouring of the concrete mixture – allowing for obtaining various colours; (3) surface pigments – acid-based preparations, also influencing the texture of the concrete; (4) aggregate colour. The concrete texture is determined by: (1) stripping – absorbent and porous structure will be reproduced in the concrete; non-absorbent and smoothed materials are used in order to obtain smooth texture; (2) shaping of the concrete surface following the removal of the formwork – in order to expose the aggregate used in the mixture, acid-etching and sandblasting are performed; in order to add texture mechanically, scabbling, bush-hammering and grinding are performed; in order to smooth the surface, polishing is performed [8].

The use of inner insulation requires analysis of the building physics elements, energy performance and heat and moisture conditions. Proper design with regard to the thermal insulation of floors, walls and roof is not fundamental here. The issue is the possibility of water vapour condensation in the outer wall or in the roof, i.e. analysis of the so-called dew point. If the outdoor temperature is markedly lower than the indoor temperature, indoor water vapour may condense in the composite wall. The traditional structure of an inner masonry wall (layer with a high heat transfer coefficient) and outer thermal insulation (layer with a low heat transfer coefficient) allows for preventing vapour condensation. In that case, the temperature of the structure is similar to the indoor temperature and the highest amplitude is observed inside of the thermal insulation layer. However, if the order of the layers is reversed, the thermal insulation will keep the thermal energy indoors. The structure will have a temperature similar to the outdoor temperature. The water vapour permeating from indoors outwards may condense on the inner face of the structure. In order to prevent this, an additional vapour control layer is applied on the inner side.

Plastic vapour barriers or technologically advanced membranes are usually used as the vapour control layer, and gypsum boards are usually used as the finishing layer of the walls and roofs. Making each layer separately carries the risk of errors and inaccuracies. Punching failures and crevices may enable water vapour penetration. Commercially available systems, e.g. composite boards with thermal insulation, vapour control layer and finishing layer made of plasterboard, are more advanced. Impermeability is obtained by affixing the boards and filling the joints with a proper grout. Another method for inner wall insulation is to use mineral insulating boards made of a light variant of cellular concrete (e.g. Multipor) [9]. They are characterised by their high thermal performance: their density can be as high as 115kg/m³. This technology allows for natural drying up of the wall on an annual basis, by systematic evaporation of the moisture accumulating in the wall structure. The material does not lose its properties upon contact with water and prevents build-up of moisture on the outer supporting wall.

Prevention of water vapour condensation in the wall or in the roof does not solve all of the problems of such building. The impermeability of the outer shell of the building necessitates the use of ventilation, preferably continuous mechanical ventilation. It allows for carrying the excess water vapour outside and for outside air to be supplied inside. Ventilation, in addition to moisture regulation, should provide heat recovery. In a compact, impermeable building with good thermal insulation, the energy efficiency is largely dependent upon recovery of the heat from the ventilation.

4. Case study

An example application of the outer reinforced concrete structure with inner thermal insulation technology is a construction plan of a small dwelling house (figure 3). Here, the technology influences
The architectural form of the building, and the architectural form influences the distribution of functions. The outer reinforced concrete structure forms a tube with an orthogonal projection and section resembling an archetypical sloping roof house. The glazing on the southern part of the living room constitutes a gable wall. The opposite, northern gable wall is a light infill wall with a glazed entryway and admits natural lighting into the attic. On the ground floor, there is a living room with a kitchenette, bathroom, draught lobby and hallway with a staircase. On the upper floor, there is a bedroom and a study on a mezzanine.

The building has a prefabricated reinforced concrete structure 20 cm (7.9in) thick. It is comprised of two parts, which are transported separately and connected with structural joints. One part is the ground floor and walls, the other is the attic walls and roof. The sizes of the prefabricated elements slightly exceed the dimensions of a standard vehicle. This necessitates additional permits and payments, albeit small ones.

Multipor light cellular concrete (version 1) or extruded polystyrene XPS (version 2) slabs constitute the thermal insulation of the walls, roof and floor. Gypsum boards are the internal finishes of the walls and roof in version 2. On the thermal insulation of the floor, there are commercial dry gypsum board screed and laminate floor planks flooring. The internal separating floor is timber-framed, which reduces the thermal bridge problem. The service lines have been provided for through the opening in the floor. The building has a water distribution system, drainage system, premises wiring and internal space heating system, as well as mechanical recuperative ventilation. The intake and exhaust vents are located in the gable wall. The building has been designed in a simple manner in order to ensure continuity and impermeability of the outer structure and to avoid unnecessary punching failures of the structure and complicated details.

Figure 3. Design of the residential building ‘Tubular House’: A – ground floor plan, B – first floor plan, C – building form view

The thermal and moisture analysis and calculations were conducted with the use of the computer programme ArCADia-TERMO PRO 6.6 by INTERsoft. In the first version the insulation made of mineral insulating plates of the lightweight cellular concrete Multipor were used. For the walls and floors the insulation width was 20 cm, and for the roof 25 cm. For such an insulation and reinforced concrete construction the width of 20 cm was obtained as a result of calculating the heat transfer coefficients: for the floor and walls $U=0.20 \text{W/m}^2 \times \text{K}$, for the roof $U=0.16 \text{W/m}^2 \times \text{K}$. The analyses
and calculations conducted illustrated that the floor, wall and roof were designed correctly in terms of avoiding the growth of mould and condensation of water vapour. According to the assumptions of this solution, moisture accumulating in winter on the wall and roof dries on an annual basis. In the second version the thermal insulation made of extruded polystyrene XPS 25 cm wide for the floor, the walls and the roof was used. For such an insulation of the reinforced concrete construction the width of 20 cm was obtained as a result of calculating the heat transfer coefficients: for the floor and wall $U=0.13\text{W/m}^2\times\text{K}$, for the roof $U=0.14\text{W/m}^2\times\text{K}$. The analyses and calculations conducted showed that the floor, the wall and the roof – which is important, even without a vapour barrier – were designed correctly in terms of avoiding the growth of mould and condensation of water steam. In the first version, the cellular concrete allows to finish the walls and roof with the use of interior plaster in an easier way, and also enables easier performance of wall chases or fixation of objects to the walls. In the second version insulation needs to be covered with gypsum and cardboards panels, which causes problems with the assembly of frames connected with the puncture of thermal insulation and a possibility of appearance of thermal bridges.

5. Results, discussions and conclusions

When presenting the design which uses the outer structure and inner insulation technology, the research was focused on the simplest solutions and on the basic problems of the building. The analysis and case study conducted have shown that it is possible to use this unconventional technology and to shape the architectural style associated with it. Lastly, it is worth discussing the advantages and disadvantages of the design proposed.

The basic advantages of the design may be the economics and mobility of the building. The construction costs may be lower than those of comparable buildings. This is due to reducing the earthworks and exterior wall finishing to a minimum, and due to the ability to prefabricate the elements. The simplicity and continuity of the structure allow for a continuous thermal insulation and for limitation of thermal bridges. This has a positive impact on the building energy performance and reduces the heating costs. The external structure allows for moving the building. It may be treated as a temporary building. The foundation slab is not connected to the ground, which allows for locating the building on underground services or in more difficult ground conditions.

Taking the costs into consideration, it appears that only simple forms of such building could compete with other technologies. The technology itself is problematic in terms of the building physics. Complex forms generate additional potential problems. Both the technology adopted and the form resulting from it have an effect on the functional limitations. The design is suitable chiefly for small buildings. This is due to the span of the structure and due to its ability to admit natural light inside. The building requires the use of controlled ventilation. Due to its impermeability, the building is susceptible to the so-called sick building syndrome. The low heat accumulation capability of the walls and roof is unfavourable in terms of energy performance. The land transport mobility is limited by the outline dimensions and weight. The building is heavier compared to other technologies, e.g. timber.

To summarise, the initial theoretical analysis indicates that the design proposed is feasible. However, further theoretical and practical research must be conducted with regard to its practical applications. Subsequent stages should include: detailed study of form for a specific function, detailed design, and then construction of a test building and operational testing thereof.

Acknowledgment

The authors thank Mariusz Gibas for his help in making thermal, moisture and energy calculations.

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