LIGHTWEIGHT STRUCTURES in CIVIL ENGINEERING
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THE LIGHTWEIGHT STRUCTURE OF BUILDINGS FROM SANDWICH PREFABRICATED ELEMENTS

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ABSTRACT: This paper describes the structure of buildings constructed from prefabricated lightweight three-layered (sandwich) units. The outer layers perform a structural function, the middle layer provides insulation, but also performs a load-bearing function. The space in the inner (core) layer is used to run building utilities. The prefabricated units are characterized by very high stiffness at relatively light weight and very high insulating power. Thanks to the light weight and rigidity of the whole structure, such buildings can be erected on poor load bearing capacity soils. The system can also be used to safely extend the existing buildings upwards. The systems of joints between the prefabricated units have been so designed as to ensure a uniform sandwich structure free of thermal bridges. During assembly glue joints are made in the inner layer. The outer layers are also glued together in order to fill the prefabricated units. This solution is patent protected (Ref. 1).

Keywords: buildings, prefabricated sandwich units, lightweight structure.

1. INTRODUCTION

The construction technologies used to erect typical enclosed buildings have remained essentially unchanged for decades. In most cases construction materials characterized by heavy weight per volume are used. The construction process is based on the craftwork of workers on the building site. The excessive, often hidden, costs in the construction industry are a barrier and a burden to sustainable development, especially to the availability of housing. New innovative construction technologies and systems enabling the economic and environmentally sustainable realization of buildings and their environmentally neutral operation are needed.

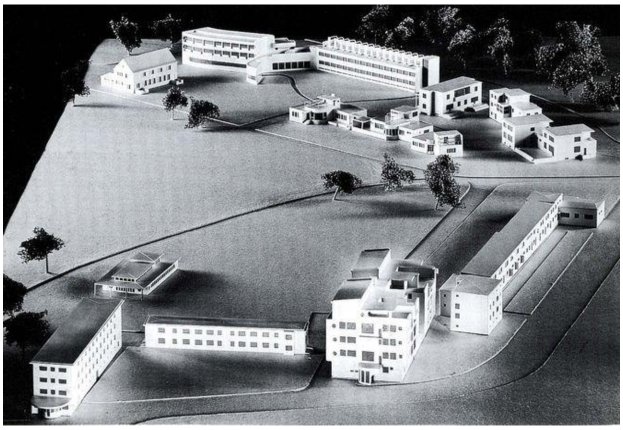

Fig. 1

An example, here are the model residential developments WUWA (*Wohnungs- und Werkraumausstellung)* in Wrocław (Ref. 2), i.e. flats and workplaces built in 1929 (Figure 1) and WUWA2 proposed since 2016 (Figure 2). A comparison of the two concepts shows that the construction technologies have remained essentially unchanged. It is apparent that the building development density in the contemporary construction concept has clearly increased.

Fig. 2

The innovative Swallow Building System (SBS) (Ref. 1) presented in this paper is based on prefabricated sandwich units of the SIP (structural insulated panel) type. In its essential and key features the SBS differs from the systems and products made of SIPs. The systems based on SIPs differ in the material of which their insulating core and facings are made, but above all in the way in which the panels are joined together. Buildings constructed from SIPs require an additional supporting structure. Thermal bridges occur in the places where the panels are joined together. Both the exterior and interior surfaces require additional insulating layers and finishing.

Figures 3 and 4 show examples of building construction solutions using SIPs. The joints are made using conventional (screws and nails) and patented joining techniques. In the solutions revealed by US Patent 5497589 (Ref. 4) and US Patent 2016/0208489 (Ref. 5) metal connectors are used to join the panels. In this case, the structural continuity of the cross section of the space-dividing elements is not maintained. The surface of the walls needs to be additionally insulated/finished.

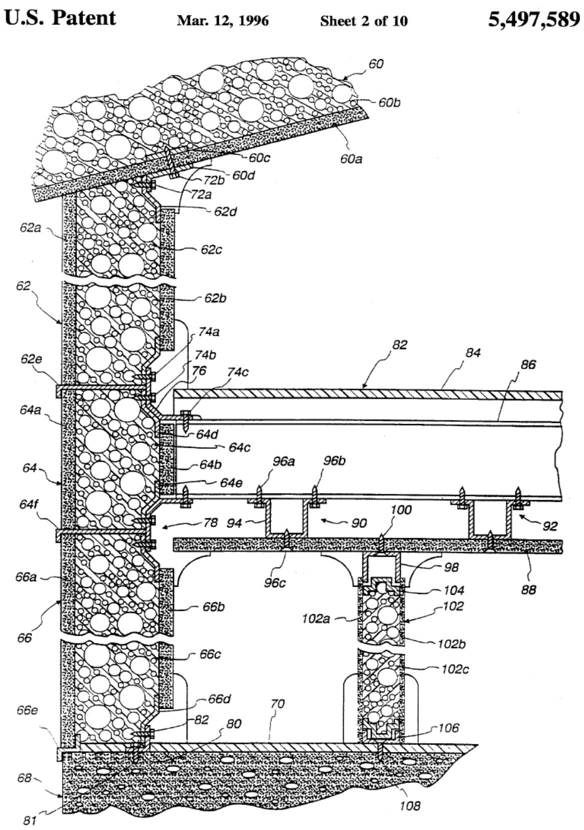

Fig. 3

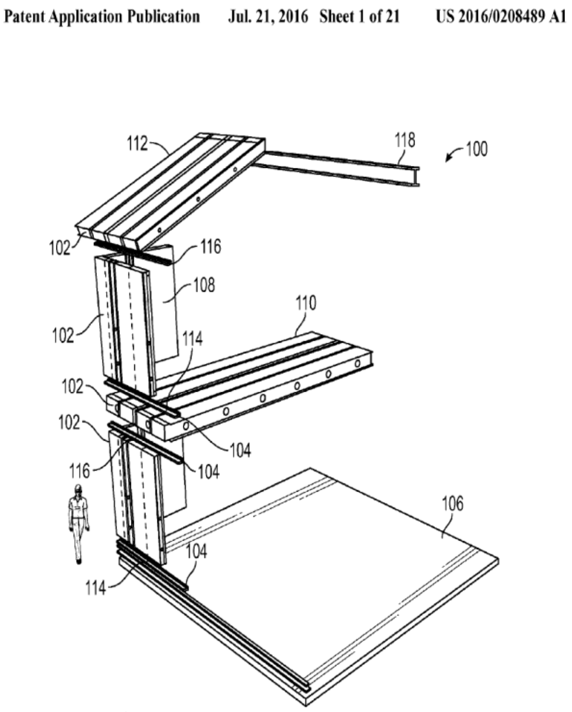

Fig. 4

In the Kingspan TEK building system solutions (Figure 5) and the ones covered by US Patent 204/005348 wooden elements (Figure 6) and conventional joining techniques are used to join the panels. Thermal bridges and the absence of structural continuity are particularly visible in the vertical cross sections and in the panel joints in wall corners. In these solutions also the building envelope elements need to be additionally insulated and finished.

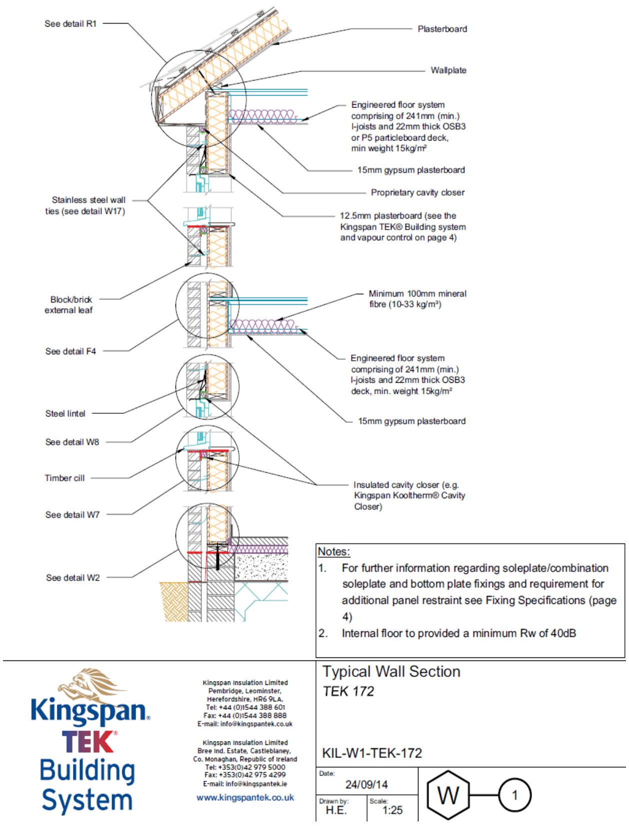

Fig. 5

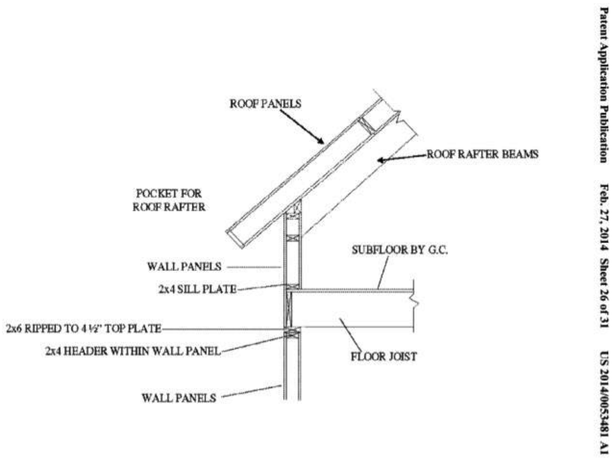

Fig. 6

In order to reach the European average concerning the number of flats the production of the latter should be increased from the current 150 thousand to 210 thousand per annum and this level should be maintained for the next 10-20 years. Moreover, in order to replace the end-of-life buildings, including large-panel blocks of flats, additionally about 50 thousand flats need to be built annually. This means that to achieve the goal of catching up with Europe about 260 thousand flats should be built annually. This is not feasible if the currently available technologies are used. Another barrier is the shortage of workers, even at the current number of flats built. The only real way of solving the problem is the industrial production of houses, based on prefabrication, production process automation and construction process shortening and simplification. Considering environment protection, construction time and operating costs, it should be a system of passive, preferably zero-energy, houses.

2. DESCRIPTION OF SBS

In comparison with the other systems, the Swallow Building System is distinguished by many features (described below, Figure 7). SBS is based on prefabricated large-sized segments having common:

- structural,
- partitioning,
- insulating,
- finishing features.

The thickness of prefabricated exterior wall, floor and roof units is over twice larger than that of typical SIPs, whereby proportionally higher performance, rigidity and strength are achieved. The thermal performance of the envelope components is over twice higher than that of typical SIPs. The prefabricated units are joined (glued) together in three directions (typical SIPs are joined together in one direction). SBS prefabricated units are three-dimensional (typical SIPs are generally flat) whereby buildings with a continuous structure can be realized. No additional supporting structure is needed. The structural continuity of the prefabricated units is maintained. No thermal bridges occur. The prefabricated units have in-built utility ducts.

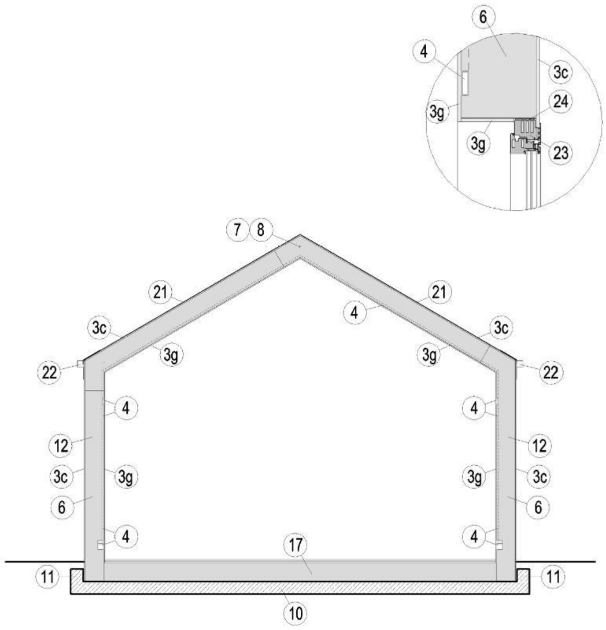

Fig. 7

An assembled building needs much fewer extra works (e.g. no additional insulation is required) and finishing works. Thanks to the relatively light weight and high rigidity of the whole structure, buildings can be erected on soils with a low bearing capacity. The system can also be used to safely extend upwards the existing buildings. Owing to the rigidity of the assembled building, forming a kind of uniform structural system, buildings erected using SBS are particularly suitable for areas with an unstable subgrade, e.g. where mining damage occurs, and especially in areas prone to earthquakes.

Buildings erected using the SBS technology are to be environmentally neutral. The whole construction process, from the production of materials, through transport and construction, to operation and recycling will be significantly less energy - and material-intensive and so more economically advantageous than the currently used technologies. After joining (gluing) the prefabricated units together a highly rigid structure characterized by very high insulating power is obtained. The walls are non-combustible and resistant to moisture and high temperature. SBS was designed as a comprehensive and open system. It is comprehensive since it covers all the aspects of the construction process. It is open since it is based on the BIM+AI technology, whereby the construction documents can be drawn up by any design office or any AI software and practically any building can be realized.

3. BUILDING STRUCTURE

Figures 7 and 8 show a general structural layout (cross sections) of buildings which can be constructed from lightweight prefabricated units referred to as the Swallow Building System (SBS). The prefabricated wall, floor and roof units are formed as a three-layer system in which the outer layers (3c, 3g) are structural while the middle part (6) performs an insulating function as well as a load-bearing function. The space within the inner layer is used to run building utilities (4). The exterior layers of the prefabricated units constitute the façade (walls) (3c) or the roof surface (floors) while their interior layers constitute the finish (walls, ceilings (3g)). The prefabricated units are characterized by very high stiffness, relatively light weight and a very advantageous heat transfer coefficient U = 0.05-0.08 W/m^{2}K. The walls are non-combustible and resistant to moisture and high temperature.

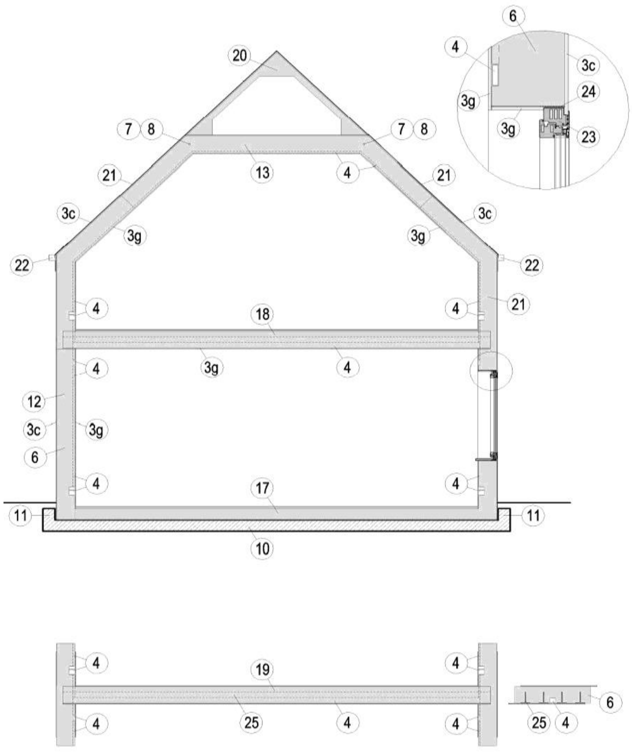

Fig. 8

The only equivalent could be a fully monolithic reinforced concrete structure containing all the building components. However, such a reinforced concrete structure is a heavy and cold (highly energy-intensive) system which requires insulation and surface finishing. SBS is characterized by a unique ratio of dead weight to load-bearing capacity (conventional building systems to a large extent carry their dead load).

SBS is by nature a warm system with no thermal bridges. Thanks to its technical parameters it significantly exceeds the standards for (passive) houses of the future, defining a new energy efficiency class. The exterior segments are characterized by very high insulating power (heat transmission coefficient U = 0.05-0.08 W/m^{2}K), which is three-four times higher than that which will be effective from 2021 (U = 0.15-0.20 W/m^{2}K).

SBS is the only prefabricated lightweight building system enabling one to comprehensively realize buildings, including (exterior, interior, load-bearing and partition) walls, floors and (flat and sloping) roofs (Figure 9). Using this technology one can realize buildings with any shape (including non-rectilinear shapes). As opposed to other forms of construction where the building structure consists of many different separate components (e.g. masonry + floors + timber-framed roofs, wooden framework structures made up of many wooden or steel components, filled with an insulating material and covered with facings), SBS buildings are rigid homogenous structures.

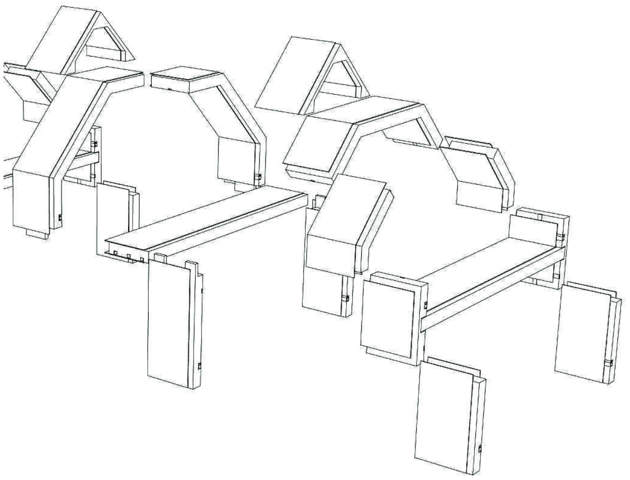

Fig. 9

When the photovoltaic technology is used, the buildings' energy demand will be balanced out (zero-/energy-plus buildings). Owing to a considerable reduction in operating costs, the saved funds can be allocated to loan servicing, which will lead to greater availability of housing. SBS is a system characterized by low energy consumption at the production, transport and construction stages, and later at the operation and recycling stages.

SBS segments will be made in a production plant. The prefabricated units will have finished (interior and exterior) surfaces and will be fitted with essential utilities and utility ducts. The segments can be manufactured for stock houses and adapted to individual design solutions. SBS buildings are characterized by exceptional rigidity and resistance to external dynamic factors (e.g. seismic shocks). Owing to its relatively light weight and the uniformity of its whole structure SBS is an excellent solution for low bearing capacity soils, vertical building extension, etc.

4. JOINING PREFABRICATED SANDWICH UNITS

The prefabricated unit is filled with closed-pore polyurethane foam of the PIR (polyisocyanurate) type. Glue joints in the inner (core) layer are made to assemble the building. The outer layers are also joined by gluing in order to fill the core of the prefabricated units.

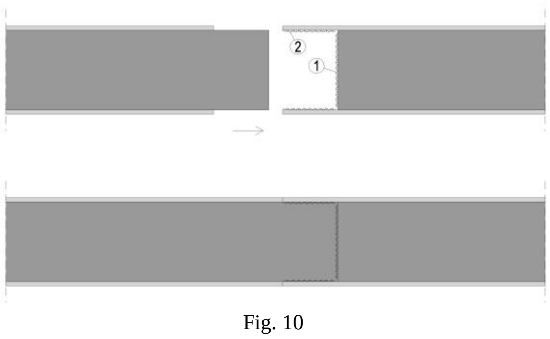

Fig. 10

The latter are joined together in three directions, as shown in Figure 10. The system of joints was so designed as to ensure a uniform layered structure. Any additional (e.g. metal) connectors used in other construction systems are avoided. This solution eliminates thermal bridges. In the places where increased static stresses occur, such as bends in the prefabricated unit shape, appropriate strengthening elements (e.g. plastic composite meshes or profiles) should be inserted.

When the prefabricated units are joined (glued) together, a very rigid structure characterized by relatively light weight and a very low heat transfer coefficient (U = 0.05-0.08 W/m^{2}K) is obtained. An additional element securing the assembled building structure is a binding cable (8) passed through tube holes made at the prefabrication stage. The place and direction in which the binding cable runs are determined by the structural considerations and the building's geometry, as shown in Figures 9 - 11.

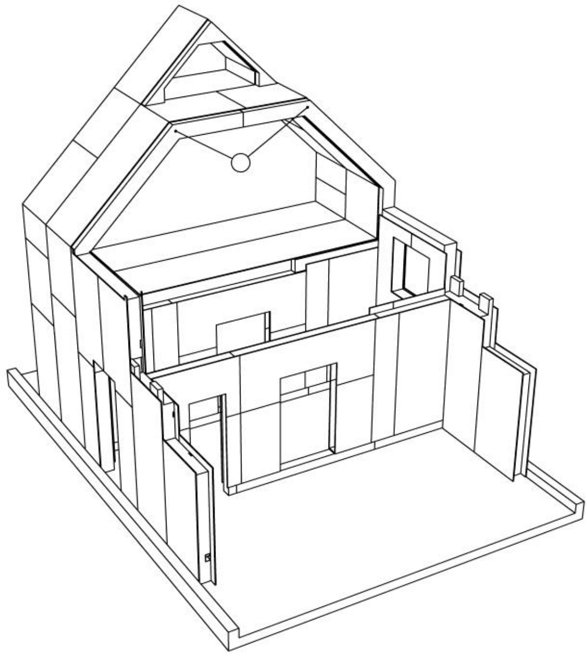

Fig. 11

The main strengthening elements of the prefabricated units are reinforcing meshes made of composites or steel, used in places of stress concentration in wall members. In the case of prefabricated floor units, reinforcing profiles made of glass or carbon fibres are used in a similar way as the reinforcement in reinforced concrete members. Since there is no corrosion hazard, such elements are glued to the outer surface of the floor member in its top or bottom zone depending on the member loading (the sign of the bending moment).

Additional prefabricated unit components are spacers, i.e. connectors in the form of a tube with an inside diameter of about 1/2'' with 20×20 cm flat plates at its both ends, whereby they can be permanently glued to the facings. They stabilize the position of the facings during production. Since they are permanently glued to the outer panels they contribute to the strengthening of the bonding of the whole prefabricated unit. For cost and technological reasons, spacers in the form of PVC tubes pressed into holes milled in the facings were adopted in the patent application. The spacers also perform an assembly function – by inserting properly shaped rods into the holes the prefabricated units can be transported, put in place and stabilized during assembly. After the assembly the holes are filled with special foam and blanked off with plugs made of the same material as the facings.

6. STRUCTURE AND CHARACTERISTICS OF PREFABRICATED UNITS

SBS prefabricated units have a SIP-like structure. Closed-pore polyurethane foam of the PIR type is used as their filling. The foam is an insulating material with the lowest thermal conductivity, whereby it meets the energy saving requirements. It is distinguished by high temperature performance and good dimensional stability. It does not rot, is resistant to moulding, does not give off odours and is harmless to health for typical construction uses. It also performs a structural function in SBS.

Prior to filling the prefabricated floor units with PIR foam (Figure 12), strengthening elements (profiles) made of, e.g., composites, glass fibres or carbon fibres, are built into them on the tensioned side. Since the strengthening elements become embedded in the structure of the PIR foam they are not prone to buckling. The outer layers constitute the final finish of the building, both inside and outside. It is possible to use panels with any finish and also to apply any additional surface texture made of, e.g., ceramic tiles, brick, aluminium, etc. The prefabricated units are equipped with utility ducts. Since the assembled building is highly rigid, forming a kind of indivisible shell, SBS structures are particularly suitable for areas with an unstable subgrade, e.g. where mining damage occurs, and especially in areas prone to earthquakes.

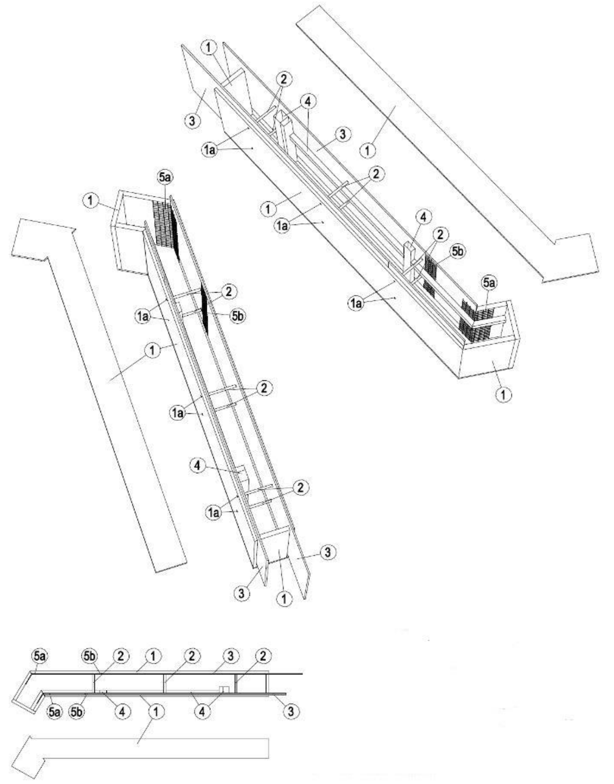

Fig. 12

In the case of load-bearing and stiffening members, the facings perform a static function. They are used as statically-bearing and stiffening liner on exterior and interior building modules. The facings provide protection against wind, atmospheric factors and enable the direct application of external plaster systems or the mounting of other finishing materials. The facings have been classified as non-combustible and belonging to reaction-to-fire class A1. Typically, the roof would be finished with white or light grey PVC sheeting, but any sheeting, e.g. roof tiles, metal roofing sheets, shingles, etc., is possible. It particularly recommended to install photovoltaic panels or membranes on the roof surface, whereby the buildings can achieve a positive energy balance.

7. TECHNOLOGY OF MANUFACTURING PREFABRICATED UNITS

The prefabricated units will be manufactured in a factory equipped with automated production lines. The parameters, shape and fittings of the particular segments will be defined using the BIM+AI software. After the owner selects and accepts a design, detailed documentation for the particular prefabricated units and the whole building, including all the fixtures and equipment, will be prepared. The manufactured prefabricated units will have built-in essential ducts and utilities.

The main advantages of PIR foams (Ref. 8) include: very good insulating properties, non-absorbability, fire-retardativeness and relatively low smoke emission while burning, enhanced thermal resistance and good dimensional stability in the whole temperature range. The characteristic distinguishing PIR foams from polyurethane foams is the ability to form char which endows the insulation with burn-through fire resistance. It is owing to the latter characteristic that PIR foams were used in the structure of space vehicles already in the 1970s. By combining PIR foams with proper fillers foamed PIR composites with the desired thermal resistance and incombustibility were obtained.

Polyisocyanurate (PIR) foams were created through a modification of the structure of the urethane polymer. Through the cyclotrimerization reaction isocyanurate rings were introduced into the macromolecule of polyurethane. Isocyanurate rings are characterized by much higher thermal resistance in comparison with the other bonds present in the polymer. The rings improved the thermal resistance of the polymer while the thermal conductivity coefficient of the foams and their water absorption remained low. Under the action of high temperature and the flame the presence of isocyanurate rings in the structure of the polymer contributes to the propensity for the formation of a solid shell (char) characterized by low heat conductivity and resistance to oxidation. The shell of char protects the inside of PIR foams against destruction and flame spread. It also improves the foam’s burn-through resistance. An important characteristic of PIR foams is that recyclable and renewable resources can be used to synthesize them. Moreover, the highly efficient equipment used to produce polyurethane foam can be used to produce PIR foams. Owing to the use of PIR foams in the prefabrication of building units the latter can be easier and quicker assembled (Ref. 8).

The production technology consists in filling shattering moulds, fitted out with exterior layers (fibre cement boards and fibrous gypsum boards) and essential ducts and utilities, with polyurethane foam of the PIR type. After the necessary seasoning the prefabricated units are formed into sets and send to the construction site. Figure 12 schematically shows how a prefabricated unit is manufactured. The prefabricated units can be of any shape – the only limitation is the cost of preparing the shattering moulds (e.g. spherical moulds). Therefore, buildings in practically any form and shape (also multi-storey buildings) can be realized.

7. CONCLUSIONS

The model of the sandwich structure of the ceiling, as in Figure 13, was tested in three ways: without any additional reinforcement, with the use of glass fiber straps, or ribs. Under the test load, none of the models were destroyed. Significant buckling occurred in the first variant and very small in the third.

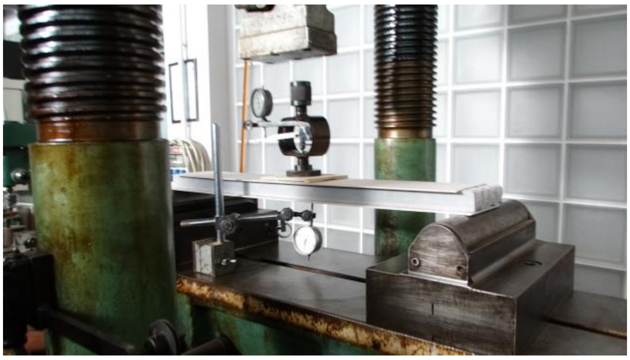

Fig. 13

The sample load of the house model is shown in Figure 14. The scale model 1:10 is ballasted with 150 kg.

The implementation of the prefabricated lightweight large-sized Swallow Building System (SBS) would result in:

- an improvement in energy security owing to the reduced energy demand (during both construction and later operation);
- slowing down the destructive and very costly climate changes;
- an improvement in the quality of the environment owing to the reduced energy demand (no pollution emissions) and to the practically waste-free production and construction processes;
- an increase in the availability of housing owing to the significantly lower operating costs;
- the realization of a greater number of buildings (owing to, the automated production and prefabrication and the shorter investment process);

- providing safe, durable, readily available and mobile mini-buildings meeting high operating parameters for persons affected by disasters and armed conflicts and needing humanitarian aid.

The SBS technology sets new standards in construction. It can become a significant innovative (Polish) product with a global reach. Owing to the very high resistance to seismic shocks, the use of the SBS technology would be particularly vital in countries prone to earthquakes.

Fig. 14

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