The Prospects of a Small-Block House Building within the Concept of the Automated Structure Construction of Residential Buildings

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Abstract. This article represents conceptual research of the issues of automation of wall construction of multistoried buildings. Initially, the authors of the article reviewed key issues arising at realization of layer-by-layer wall construction method using building printers (so-called contour construction). According to the authors, the specified problems make significant limitations in the further development of contour construction method, since they have no simple solutions within this method. In other words, the method doesn't allow to solve some specific technological issues related to the field of structural design. Authors proposed a concept of the automated small-block construction method, which allows to solve the listed issues, and also to reduce quantity of technological steps made directly on the building site. The concept borrows some practices of the existing contour construction methods (in particular, use of portal printers), by keeping unchanged the principle of small-block wall construction method. Thus the automation of the building of the walls concerns precisely the processes of preparation, delivery, and installation of small blocks in their specified position, and the associated technological processes (like wall decoration or channel making) decide due to complication of wall blocks structure. The authors of the article consider that the proposed small-block construction method will allow to optimize and accelerate processes of structure construction of residential buildings.

1. Introduction

Automation of building construction (further ‘BC’) always remains the tempting idea. However, at the way of its implementation there are a number of the essential difficulties connected with specifics of a construction technology. Construction of the building implies several operations, which are difficult for subjecting to automation. Any construction process comprises some specific actions and also uses materials, various on physical properties. Besides, parameters of the finished product (building) are subject to rather strong changes at the stage of creation of the project (distinction of designs, structure of premises). All this leads to the need of development of the technology that will allow to create flexible design decisions, and then to implement them on a construction site. In modern market conditions when ideas of optimum planning structure of the house at different customers often strongly differ, this problem is especially relevant.

Attempts to automate the methods of construction production were actively made in the Soviet Union. In particular, the ideas of panel and volume and block housing construction allowed to build
standard buildings cheap and quickly. At the same time, the quality of these buildings, subject to strict compliance with the construction technology was very high, which is a specific advantage of the automation idea. However, the ideas of automation concerned generally the production of prefabricated building constructions. Construction of buildings was conducted by traditional methods, with use of some means of mechanization (for example, hoisting appliances) and manual work. At the same time, the high speed of building construction has been caused, first, by the thought-over constructive solutions and methods of structure assembly allowing to perform all works in short terms and also the developed schedule of construction processes and competent logistics. In addition, this approach demands the well-developed industrial base allowing to create the difficult enlarged elements of the required sizes and properties. It should be noted that with increase in the geometrical sizes of these elements the quantity of possible architectural planning solutions decreases that lowers attractiveness of such an approach in market conditions.

Now attempt of partial automation of the BC is the method of planimetric construction of walls (further ‘PC’), or the so-called 3D-printing of walls of buildings. The process of wall construction in comparison with other (the foundation work or roof construction, an installation of utility networks) is the simplest for implementation by machine means, and consists in creation of the strong wall shell of certain design. For its construction, it is necessary to lay out layer-by-layer special concrete mix with use of the special working assembly according to the control program. Such an approach allows to accelerate considerably the main work on construction of vertical load-bearing structures of the building. At the same time the main accent is put on the use of the precision equipment (the so-called ‘construction printer’) managed by program algorithm. Person interaction in working process is reduced to operation control of such mechanism.

Today there are several groups, which are engaged in development of this technology. The Russian branch is provided, first, by the enterprise ‘Spetsavia’ which has implemented about three tens portal construction printers of own design for last year [1], the enterprise ‘ApisCor’, which use the original printer working in the polar coordinate system [2] and also the personal development ‘StroyBot’ of Andrey Rudenko[3]. Also the USA finances Dr. Behrokh Khoshnevis's project, known as ‘Contour Crafting’, combining the walls formed by 3D-printing method with horizontal load-bearing prefabricated structures [4]. China is provided by the ‘WinSun’ company, which has created in 2014 ten simple printed buildings per day and the 5-storey building and the mansion one year later [5]. There are also other projects using the PC method.

Despite obvious progress, this approach to automation of the wall construction process has some serious difficulties arises from the specified PC method. Let's consider them consistently.

1.1. Issues of the planimetric construction method

1.1.1. Lack of a regulatory standards and the elaborated calculation theory of the load-bearing structures received by the PC method

The walls built by the PC method represent the thin-walled sandwich concrete constructions having the specific properties directly connected with technology of their production. There is no regulatory base controlling the wall construction process by such method today. It is required to attract the specialists directly involved in implementation of this technology to draw up such documents. The experiments and the experimental data on upkeep of buildings with such walls including approval on the theory of calculation of such designs with practical results of their tests are necessary.

Now the 3D-printing method is used mainly for construction of the low-loaded walls of the single-storey buildings that allows to use them as vertical load-bearing structures. At construction of the multi-storey buildings by the specified method, the role of such walls comes down only to retained shuttering. Creation of any vertical load-bearing structures inside the printed shell should provide the installation of the reinforcing cage, which will be further filled in with cast-in-place concrete. Thus, the full automation of BC on this issue is still difficult.
The listed problems relate to the calculation and design of the printed buildings, and here it is about lack of necessary theoretical base. For the printing of building cores use the concrete mixes modernized in a special way (for example, with addition of fiber and also the additives considerably increasing viscosity and accelerating setting), i.e. very specific material, which properties differ from the structural concrete or cement mortar mix. The behavior of such material during the long operational cycle is unknown.

1.1.2. Specifics of the structural materials used within the PC method

Unlike the methods of construction using prefabricated elements with the known physical characteristics, preparation of concrete mixes by the PC method conducts directly on the building site that requires some additional measures for quality control of the feedstock used in on-site work.

Concrete setting and wall material maturing also occurs on the building site that imposes some restrictions for conditions in which the structure construction proceeds. In particular, maintaining the concrete mixes maturing process demands to set constant temperature and humidity conditions on all volume of the created object and to provide protection against rainfall for a significant period. Observance of the listed measures can be difficult feasible in manufacturing conditions and during the wintertime is capable to lead to considerable complication and rise in price of the BC process.

Quality control of the final product (wall) received by the PC method is also complicated. Strictly speaking, it is impossible to be certain that material of a load-bearing structures of the building will sustain the loadings arising at its further operational cycle. The problem can be partially solved by using non-destructive methods of strength assessment of the obtained material. In case of destructive assessment methods, it is necessary to provide the special sites of walls intended for sampling.

At construction of walls by the 3D-printing method, some difficulties connected with technology of their production also arise. The PC method uses the principle of layer-by-layer viscous concrete mixes application. At the same time overlying layers transfer the loads to underlying that can result in ‘elephant leg’ effect, shown in the thickening of the lower layers of the printed structures and also to the wall subsidence during the building process. Shrinkage of the lower layers, in turn, leads to a hardly noticeable increase in the height of the new freshly placed layers stacked by the printer’s working assembly. It is difficult to track this process, so the used concrete mix must have high viscosity, as well as the minimum possible terms of setting. Parameters of this mix, in particular water-cement ratio, must be continuously traced by electronics and supported at the constant level, which complicates the design of the printing unit and the related devices.

To ensure high-quality extrusion, the concrete mixes used within the PC method should have sufficient plasticity. Despite the use of plasticizers, such mixes will have rather high water-cement ratio that lowers the final strength of the constructed walls. At the same time, even at the minimum plasticity of the mix, there is objective restriction for total height of the wall made in one go. Therefore the building should either be printed with a breaks for a concrete mix setting, or built in parts, making final assembly by the mechanized means (with the crane hoists). Thus, the very principle of construction using flexible concrete mixes imposes essential restrictions on the prospects of the PC method to make the load-bearing structures of buildings. The alternative solution is the print with use of special fast-setting mixes; however, such mixes can use expensive components that increase the cost of the final product.

1.1.3. Structure strength and prefabricated elements usage

Here it is about horizontal, vertical, and crosswise reinforcement of the printed walls. The traditional wall made of small blocks represents rather solid body, in which volume the armature located in the horizontal plane has high (often absolute) coupling with the concrete mix surrounding it and, consequently, the material of the walls. In case of printing walls with extensive internal air voids, such coupling can be provided in the edge layers only. In the very wall, volume armature will cross the inner bonding concrete planes rather seldom. Under the influence of any kind of loads (in particular, vertical ones) at such points, local stresses, presumably exceeding those in traditional walls at times,
will occur. At destruction of concrete in these points, the stresses will accumulate in other similar places, which can ultimately lead to fast consecutive destruction of all building core.

Within the PC method, the problem of wall reinforcement also requires automation. And if in case of crosswise reinforcement this issue can be solved by providing the working unit with the special mechanism with armature stock, then in case of horizontal and vertical reinforcement it is essentially impossible to solve the problem owing to features of the 3D-printing method. Such reinforcement works should be done manually.

It should be noted that the building core, built by the PC method, represents the monolithic structure in which the process of stress and shrinkage cracking are of great importance. The use of viscous concrete mixes for construction and weak reinforcement of the received concrete monolith is capable to lead to the formation of a number of difficulty predictable cracks including those occurring in the adhesion areas of wall layers. Thus, the cracking formation development and its impact on load-bearing ability of thin-walled concrete structures require further examination.

The difficulties of a constructive nature also include the installation of various kinds of lintels for window spans and door openings, as well as floor joists. It is impossible to print them in a project position for obvious reasons, and therefore it is necessary to use prefabricated elements, placing them manually. Moreover, even with a sufficient viscosity of the concrete mix from which the walls are printed there is a danger of local crumpling of the printed layers in the bearing areas on the walls. Strictly speaking, the installation of any prefabricated structures transferring high dot loads to the walls can be made only after the material of these walls reaches the required strength. Such nuances considerably slow down the wall construction process and reduce the attractiveness of the PC method for construction of buildings more than one floor high.

1.1.4. Exterior and finishing of the walls. Climate impacts and heat engineering of the walls

The raw walls erected by the PC method have a specific structure not too attractive externally. On the one hand, such a surface is a hallmark of the method, on the other - it usually requires two-sided finishing. It's necessary to provide wall surface plastering or other methods of wall finishing within the PC building method. Finishing works can be performed with use of sheet material (inside the building) or building-based hinged facade (outside). In this case, the automation of wall construction process does not solve the problem of high-quality finishing, and such works should be done in a traditional way, using manual labor.

It should also be noted that, in difficult climatic conditions, the cracked structure of the raw walls can be damaged and subsequently destroyed by alternating freezing and thawing processes. Thus, the outer surface of the walls requires some protection from weather influences and a certain temperature conditions.

From the point of view of the heat engineering, the wall constructed with the PC method represents the solid structure with air voids and extensive cold joints in the form of the thin concrete inner connecting membranes. For this reason, the most rational way of heat protection of such a wall is a continuous covering of its outer surface with an energy efficient insulation. Heat protection and finishing of walls can be implemented by any kind of hinged facade system. Therefore, all facade assembly works will have to be performed in a similar traditional way.

Thus, the considered above PC method has several problems connected with the unreasoned extrapolation of the FDM printing technology to the field of building construction. Undoubtedly, this technology allows to simplify and speed up the building core construction process, but at the same time some unobvious difficulties considerably reduce the applicability of the final product.

Comparison of the PC method with the FDM plastic printing method is not accidental. With a small print size of tens of centimeters, many moments (such as the object material properties, the quality of its surface, the accuracy of printing, etc) satisfy the requirements imposed to such work (primarily strength and aesthetics). However, with an increase in the size of object and change of the material used for the print, this technology no longer provides the required results.
To use the printed objects in any industry the printing technology must meet the specific requirements of this industry. In case of BC it is the structural strength, stability, crack resistance, heat engineering properties, technological effectiveness, fire safety, utility systems installation possibility, maintainability, aesthetics and some other. In other words, the PC method should be either adapted to these conditions or seriously changed, which will allow to eliminate the listed inconsistencies to the requirements of the building construction industry.

The authors of the article propose for consideration a possible concept of the automated load-bearing structure construction of the buildings, which meets such requirements.

2. The concept of the automated block construction
The concept of the automated block construction given below (further "ABC") implies a withdrawal from the direct print of walls by PC method towards the use of the wall blocks and other structures that have known sizes and physical properties. Such an approach allows to solve the described above number of specific problems of 3D printing method.

The main difference of the provided ABC method consists in change of construction technology of load-bearing structures. Within this method, the working unit, which is directly performing installation works, is represented by the robotic device equipped with special mechanisms of hoisting, fastening and transporting of the prepared structures.

Placing of the structures in the permanent position is carried out by working unit automatically. The ABC method also provides the automated delivery of structures to the working unit of the construction printer. If necessary, some part of the delivery or mounting works can be made by the operator.

2.1. Vertical load-bearing structures assembling
Knowing the features of the wall blocks (for example, compressive breaking strength), it is possible to be sure that the built wall will be capable to perceive design loads. Besides, the invariable blocks sizes guarantee the constancy of geometry of these walls. Such view allows to gradually control the quality of construction at all stages, from the production of blocks and the works of structures mounting.

When constructing the walls with the use of small blocks the requirements to the structure and physical properties of bonding concrete mix are slightly reduced (in comparison with the PC method). Now the function of this mix is confined to the general fixation of the installed blocks into the solid wall body. Application of quick-setting masonry mortars allows to reach the design strength of the built structures directly during the construction works that provides the continuity of the construction process for any number of floors of buildings. The wall received by the ABC method has no differences from the traditional brick wall, and therefore known techniques of calculation and design, corresponding to the existing regulatory base, are applicable to it.

Within the ABC method it is possible to mount any vertical modular structures, both bearing (walls or columns) and non-bearing (partitions). The different functionality of such structures allows to optimize the weight of the obtained building core due to active density variation of the used small blocks. The bearing wall blocks and parts of columns can be made of high-density structural concrete, and the partition blocks - of lightweight aggregate concrete. To perform several functions simultaneously these blocks can be created from concrete of different recipes and have various kinds of protective, insulating and decorative coats. In particular, it applies to the blocks of the outer walls, which perform a number of functions on ensuring load-bearing capacity and structural stability of the building core, heat insulation of its internal volume, and protection against climatic influences.

2.2. Horizontal load-bearing structures assembling
The continuity of BC process can be also provided at installation of any horizontal structures, such as door or window lintels, different beams of prefabricated floor systems and other constructions.

Building floors may be represented by different types and materials, but all of them should use the enlarged modular constructions of known sizes prepared for the mounting within the ABC method.
Each beam floor element must have special key points (service openings), for which it can be fastened and then set in specified position.

It is important to note that the erection of the second and subsequent floors of the building is possible only with the provision of some measures for fastening the vertical load-bearing structures in the horizontal plane and ensuring their stability. In most cases fastening of walls is provided with the floor structure design. When using different kinds of beam floors the assembled horizontal load-bearing structures must be connected with the existing walls of the underlying floor with some anchor devices. Also, to ensure uniform load transfer from floor beams to walls, in basic perimeter usually arrange a number of the load distributing structures (bedplates).

Within the ABC method both of these problems can be solved by applying special 'bathtub' wall blocks, containing reinforcing meshes, anchor devices and bedplates for the beam support sites. Such blocks will allow to fix beam support sites in the wall perimeter and distribute their loads to the underlying wall layers. During the installation of beams on such blocks they are filled with a fast-hardening concrete compounds, which lock the beams on the walls. Wall construction of the next floor can be continued directly after the completion of these operations.

Lifting of floor beams to the required height and mounting them in the project position is performed by mechanisms of the working units, which combine hoisting appliances and robotic gripping devices. Installation of the heavy enlarged elements should be implemented by several working units, operating simultaneously. Some operations related with the lifting of structures by hoisting devices can be done with direct participation or the operator, but after fixing of the elements by the gripping device of the working unit their installation in permanent position always occurs automatically.

2.3. Organizing of the building construction complex within the ABC method

Considering the stages of a load-bearing structure construction, it is possible to allocate several operations performed consistently for any part of the wall. First, it is the preparation of the element (for example, applying a mortar mix on it), then the delivery to mounting point, and finally, its installation in a proper position followed by vibrocompaction and finish of seams between the elements. Thus, within the construction complex intended for the erection of the building core, it is possible to allocate at least three key means, the implementation of which depends on method details.

2.3.1. Structure Preparation Means (SPM)

Within the ABC method, it is necessary to provide a special area where the building structures will be prepared for the further mounting. Each element is processed the same. Preparation consists in checking the key element sizes and applying a certain amount of a mortar mix to its sides. Further, the element moves to the 'contact pad' representing the special section of the construction site used for transfer the prepared structure to the next means of the construction complex.

2.3.2. Structure Delivery Means (SDM)

The ABC wall forming method uses structural components of different shapes, sizes and weight. These parameters determine the intensity of the elements delivery to the printer working units that perform their direct installation in the project position.

Lifting of the floor beams, as well as the other elements of large sizes and weight can be implemented using compact hoisting devices (hoists), which are the part of the printer working units. Working simultaneously, these hoists perform all lifting works of large-size prefabricated element with further placing it on receiving 'contact pads' of working units. These pads are necessary for the rigid fastening of the element for the purpose of further installation it in the project position.

With a reduction of the size and weight of the discrete elements, such an approach to their delivering to the required height loses its productivity. One of the solutions of this problem is using the flying cargo platforms (copters) of high payload, managed in fully automatic mode. This unusual decision allows to considerably increase the final mounting intensity of the used structures, as well as
completely abandon the other ways of delivery of the materials necessary for the assembly works at heights (that is especially important in the field of multistorey BC).

It should be noted that the large structures delivery can be also performed by several copters working in conjunction. Research work conducted with the group of engineers under control of the expert in the autonomous systems Raffaello D'Andrea [6], shows that the principal possibility of using the copters for high-precision cargo transportation within some space volume exists already today.

2.3.3. Structure Mounting Means (SMM)

The working unit by the ABC method represents the robotic device containing a special 'contact pad' intended for the reception of structural components. This pad is supplied with the gripper, which allows to lock the given elements and set them to the specified position, the vibrocompaction device leveling the mounted elements, the finishing means, and the other auxiliary machinery. To implement part of the work on lifting the elements by a mechanized way, the unit also has a built-in hoist.

Advantages of such approach are maximum accuracy and high freedom of structure positioning. During installation, the element can be deployed in any direction that allows to create flat arch lintels as well as to build wall structures of any configuration. In this case, the difference in a masonry seams thickness is determined by the amount of the mortar mix dosed by the SPM.

It is important to note that the installation of wall blocks with simultaneous grouting of seams allows to completely refuse the works connected with the further finishing of walls and also to minimize volumes of interior finishing. In case of use of the wall blocks comprising the elements of a facade systems (an insulation and the finishing layer), the result of such a masonry will also conform to thermophysical and aesthetic requirements. The type of front finishing does not depend on the base design of the wall blocks and can be varied (artificial stone, aluminum panels, plastic). In addition, the erection of the facade system in parallel with the wall construction excludes the possibility of its geometrical distortion.

One of the main advantages of the described method consists in the full refusal of a manual labor during the assembly of external finishing, since all this work is performed in parallel with the process of the wall construction.

2.3.4. Working Units Positioning Means (WUPM)

Despite the design of the working units, both methods of wall erection (PC and ABC) need to use of a unified way of the positioning implemented by a large-scale printer device working in a rectangular or polar coordinate system. The printer represents the temporary engineering construction built by traditional methods with use of crane hoists and manual work.

The main drawback of such approach consists in high labor input of assembly and dismantling works. On the other hand, this method of positioning is reliable, visually simple, and provides high accuracy of work, so is the most acceptable now. Since the height of the building exerts a direct impact on the WUPM support, optimization of its design for construction of multi-storey buildings is of the greatest interest here.

At construction of the multi-storey buildings, it is reasonable to bind the WUPM to the building structure by the supported tower crane principle, thereby providing its structural stability in the horizontal direction. Considering the fact that the wall, built by the ABC method, acquires sufficient strength already during the construction process, WUPM can use it for the further work and movement, transferring its weight to it.

This design can be made in the form of a quadrangular frame representing the top level of the portal printer. This frame is located horizontally, forming a rectangular area, where the working units move. During the construction of the building, the frame goes up, allowing the working units to create the next level of the object's wall perimeter. At the same time, the support parts of the frame always transfer their loads of the last built level of the walls at the points provided by the project.

Lifting of the WUPM frame is provided by special sliding supports, working alternately. Filling the wall plots with blocks near each support is possible only when the support is in the raised position and
does not transfer the load from the printer frame to the underlying load-bearing structures. Therefore, in order to avoid loss of strength and structural stability, the printer design should mean a number of such supports, any of which can be raised separately at any time.

At construction of multi-storey buildings in a frame constructive system, functional differences of the used blocks are of particular importance. For example, the load reception and transfer can be performed by the components made of structural reinforced concrete. At the same time, the non-bearing external and partition walls can be implemented by the lightweight wall blocks. Also, much attention should be paid to the coaxiality of the supporting structures, providing constant control of the printer frame position in the horizontal plane.

At construction of low-rise buildings (2-3 floors), the WUPM can be made according to the traditional scheme of the portal printer on four pillars, or in a different way, implying a self-supported design. Such a printer can be developed by the principle of the self-mounted or jib cranes that excludes the use of other hoisting equipment on the building site and reduces the cost of the BC process.

For the construction of small buildings the WUPM can be represented by a modular prefabricated metal structure equipped with the built-in winches and control mechanisms. Assembling and configuring the WUPM into working position is performed on the previously prepared railway tracks set along the existing foundation of the future building. Ready to work device resembles a gantry crane, equipped with a bridge beam, capable to move along the supporting pillars and providing access to any level of the masonry plan of the future building. The working units attached to the bridge beam carry out all the installation works on construction of load-bearing structures, sometimes performing the functions of mechanized hoisting appliances.

Thus, the optimization of the WUPM for the erection of building structures consists in a partial reconstruction of the portal printer design in order to preserve its main advantage (high accuracy of the working units positioning) and eliminate the key drawback (the need of mounting of the temporary support pillars). Within the specific objective, various constructive designs are possible, but all of them should imply the construction of the WUPM support structures by the printer itself.

3. Conclusion

Despite the gradual distribution of the 3D-printing method into the field of building construction, some obvious shortcomings complicate its further use. The main problem of this method is the isotropy of the objects produced on its basis, which does not allow to properly separate building elements onto bearing, non-bearing and enclosing that, in turn, results in need for additional works. First, it is the structural reinforcement of the printed objects (implying creation of the solid columns directly on the building site) and also manufacture of the prefabricated elements (lintels, floor joists and the other beams), installed traditionally and do not fit into the scope of the method. Secondly, it is the front and finishing works, the automation of which represents a complex engineering issue.

These and many other problems described above can be easily solved within the provided ABC method, using the traditional building technologies improved with the modern automation tools. Further development of this method will allow to create the construction complex that has serious advantages over the existing methods of traditional and planimetric construction.

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