Improvement of Structural and Technologies Solutions for Erection of Flat Slab Buildings

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Abstract. The object of this research is frame systems with concealed girders and flat floor slabs. The research helped identify the main advantages and disadvantages of precast/cast-in-situ frame systems for the construction of flat slab buildings using modular elements. The key methods used in the research were the analysis of the existing domestic and foreign technologies and the development of a new structural system differing from the systems discussed in the paper in terms of its technological intensity, versatility of application and rational design. The authors suggest a precast/cast-in-situ frame building system with concealed girders and flat floor slabs where the volume of modular precast elements drastically exceeds that of the cast-in-situ part of the frame. This allows for considerable saving in assembly and erection time due to a reduced number of process operations and modular assembly units. In order to identify the key benefits, the suggested frame system was compared with a KUB 3-V multi-purpose beamless frame system, which has been popular in Russia in recent years. Apart from a smaller number of process operations, the new system allows reducing the scope of welding and removing embedded parts connecting shells of drop panels with the bare part of column reinforcement. It also eliminates the needs for additional installation fixtures for columns and floor slabs, such as: support brackets and conductors for each column. The envelope of a building using the suggested frame system may consist of semi-integral thermopanels offered by domestic and foreign producers.

1. Introduction

The use of flat slabs without column heads offers obvious advantages for enclosed-space building construction varying in terms of the functional purpose, spatial layout and design of buildings [1–4]. Some foreign scientists focus their studies on the assessment of seismic stability [5–8], also for self-aligning enclosing panels [9], fire-resistance [10], and reliability of flat slabs as compared to beam slabs, when exposed to additional loads [11–13]. At the same time, the studies [3–7, 10–12], and [14] underline that the key aspect of engineering and construction of high-rise buildings with flat slabs should be the junction between the column and the floor slab, being the most vulnerable point of such construction systems.
From the architectural and layout planning perspective, the use of flat slabs allows for open-plan floor design and helps reduce the volume of a building, eventually cutting down the construction cost. In the past 10-15 years, the above advantages facilitated the application of flat floor/ceiling slabs in office and shopping centers, hotel lobbies, various underground facilities, etc. The flat slab technology without column head has become especially relevant for upgrading industrial buildings associated with improvement of process lines for manufacturing finished products, which requires flexible planning solutions.

Until recently, flat floor/ceiling slabs without column heads were thought to be common in cast-in-situ home construction [15], although there are studies [16–18] which not only refute this standpoint, but also highlight the efficiency of factory-made modular elements. The lifecycles of relevant buildings are discussed in the works [19–21]. The use of flat slabs is reported to reduce construction labor input and time, however this technology was also found to sustain all loads which arise during construction and are much greater than operating loads.

Therefore, the relevance of this study is explained by the worldwide increasing popularity of frame construction with flat slabs meeting certain criteria: reliability, environmental safety, technological intensity, architectural expressivity, and flexibility of solutions adopted at all stages of a facility lifecycle.

2. Methods
The purpose of this paper is to present a new structural system for precast/cast-in-situ frame buildings, differing from the existing systems by a rational design, technological sophistication and functional flexibility.

To achieve this purpose, the authors have analyzed the modern frame construction technologies using flat slabs, singled out the efficient solutions for interfacing structural elements of frame buildings with flat slabs, and identified technology deficient construction processes. The effort has culminated in the development of new technological solutions ensuring economic efficiency (cutting labor input and accordingly, construction time) and safety of making frame buildings and facilities using flat slabs.

In particular, based on a brief analysis of the existing design systems and systems considered in [22], a new frame construction system was offered for making hybrid precast/cast-in-situ frame buildings with flat slabs.

The suggested system consists of precast reinforced concrete columns of the lower, middle and upper tiers, girders with a length corresponding to the length of three cells, and floor slabs with dimensions corresponding to the cell dimensions. The cell dimensions depend on the adopted layout planning solutions and can be identical to those currently used in contemporary architectural and structural systems: \(6 \times 6\); \(4 \times 4\); \(3 \times 6\) meters. In the middle and upper tiers, the height of columns depends on the height of floors in the building. In the lower tire, columns are placed in foundation blocks and have a greater height. Columns are non-cantilever type with a rectangular cross-section \((40 \times 40, 40 \times 60\) cm); in the lower and middle tiers, columns have fork-shaped heads, and the upper tiers are similar to the middle ones. The lower part of middle and upper tier columns has a rectangular central reinforced concrete bar (flange) with the same profile as the forked head of lower and middle tier columns, thus providing a reliable “plug” coupling between columns and girders and between columns.

The use of a plug coupling means that a girder freely enters the column’s forked head, and the lower central bar of middle and upper tier columns also freely enters the forked head with preinstalled girder to reliably fasten it.

The suggested structural system uses precast girders with a length corresponding to the length of three cells, plus 200 mm for the parts projecting beyond the column outer contours. The wall envelope is then mounted on the projecting part of the girder (Figure 1a) resting on the end rows of columns. And the connection bars at the other end of the girder (Figure 1a) are coupled with the reinforcing cage of the cast-in-situ girder part.
The girder flanges are two-step structures (Figure 1b) supporting hollow core floor slabs, which have reverse steps at the resting points. At the junction points, girders have hollows matching the size of hollows in the forked head of columns. The “plug” coupling of the column and girders is shown in Figure 1c.

Butt joints of columns are arranged on the level of floor and girders and secured by welding cover plates on the lower projecting reinforced concrete central bars of middle and upper tier columns with embedded parts on the forked head of lower and middle tier columns.

The floor slab is a rectangular prefabricated reinforced concrete hollow core structure with dimensions of 6 × 6; 6 × 3; 4 × 4 м (Figure 1d). Because the slab thickness is equal to the girder thickness, girders seem “concealed”, thus forming a smooth flat slab for floors and ceilings.

The flat slab rests on the girder with its stepped butt end. For buildings with balconies or sun rooms peripheral floor slabs are used having a complex geometry and solid cross-section.

External walls can be made of both hinged panels and brickwork, or other energy efficient materials laid over floor slabs. Walls can be made self-supporting and erected on a separate foundation.

Spatial rigidity and stability of the suggested framework is accomplished by rigid coupling of columns, girders and floor slabs (Figure 2) due to grouted junctions between these structural elements.
As enclosing structures, the envelope may use energy efficient SPANS thermopanels, as they are suitable for precast/cast-in-situ beamless frames. Besides, the hundred-percent installation readiness of thermopanels allows for a significant saving in material and labor input.

The major part of process blocks (sub-cycles) do not have principal differences from the conventional construction technologies. Frameworks with “concealed” beams are installed as structured module where the crane works towards itself, i.e. from the farthestmost to the nearest cell. The process flow of installation of structural elements includes: lower tier columns farthestmost from the erecting crane, then the nearest columns, then girders and, finally, floor slabs. The same sequence should be followed to install the structural elements in the middle and upper tiers.

This combined pattern of construction works not only ensures stability of the tiers and the building as a whole, but also provides for welded and grouted junctions of structural elements, with cast-in-situ parts of “concealed” girders (Figure 3).

![Figure 3. Cast-in-situ parts of “concealed” girders](image)

The columns are installed considering the structural specifics of the elements themselves: lower tier columns are placed in foundation blocks and the junctions are immobilized using the conventional technology; lower and middle tier columns and middle and upper tier columns are aligned and butt-welded with the installed floor slabs. Columns are supplied to the junction point using a tower crane and any lifting gear suitable for their handling. Because the structural system in question features plug coupling of structural elements (columns – girders, columns – columns), the installation process does not require additional installation fixtures to ensure precise attachment. However, before installing middle and upper tier columns on the preinstalled girder, the coupling is grouted.

The accuracy of installation of columns and girders is controlled by two theodolites in two mutually perpendicular directions, and for unique buildings – by advanced (GPS-based) control systems.

For making cast-in-situ girder parts the lower part of the forming system with a suitable geometric form is assembled on aligned and fastened telescopic struts, with blocks placed on the deck to ensure a required thickness of the protective concrete mix layer. The prearranged reinforcing case is linked to the connecting rods in the precast girder part, and the side decks of the forming system responsible for maintaining the geometric form (i.e. stepped flanges) of the girder are secured. A specific make concrete mix is supplied and the forming system with telescoping supports is removed after the concrete layer acquires at least 70% design strength.

Hollow core floor slabs, considering the size of structural units themselves, are installed using self-balancing all-purpose slings and grouting before placing slabs on the first step of the girder flange, which supports the slab.

3. Results and Discussion
The analysis of some characteristics of frame systems [22] shows that the MBF (multi-purpose beamless frame) [KUB] system developed in Russia has been the most popular in the last ten years, and as such, was used as a reference to compare the above structural system.

The comparison (see table 1) considered the number of process operations, standard structural elements within a three-cell span, auxiliary appliances, and the opportunity to use SPANS (Simplex Panel System) thermopanels.

Table 1. Comparison of a KUB 3-V MBF system and the new system

| Parameter                               | KUB 3-V ABF system                                      | New system                                      |
|-----------------------------------------|--------------------------------------------------------|-------------------------------------------------|
| Total number of structural elements     | 29 elements (columns – 8; drop panels – 9; plates     | 13 elements (columns – 8; girders – 2; floor    |
| within three cells                      | between columns – 9; middle plates – 3)               | slabs – 3)                                      |
| Special fixtures for installation of    | Support brackets, conductors for each                 | Only telescopic struts to support the form      |
| columns and floor slabs                 | column, telescopic struts                               | of cast-in-situ parts                           |
| Additional parts for coupling           | Embedded parts connecting drop panel shells            | Not applicable                                  |
| columns and floors                      | with the bare part of column reinforcement             |                                                 |
| Welding                                 | Present                                                | Half as much                                    |
| Use of SPANS thermopanels              | Possible                                               | Possible                                        |
| Process operations (per cell)           | 1. Installation of stacked columns                     | 1. Installation of single-tire columns           |
|                                        | 2. Assembly and attachment of a support bracket on     | 2. Installation of girders                       |
|                                        | each column                                            | 3. Installation of floor slabs                   |
|                                        | 3. Installation of a conductor above each support     | 4. Installation of conductors for               |
|                                        | bracket                                                | mounting next tiers                             |
|                                        | 4. Installation of drop panels                         | 5. Installation of next-tire columns             |
|                                        | 5. Installation of telescopic struts under drop        | 6. Grouting of column couplings                 |
|                                        | panels                                                 | 7. Dismantling of conductors                    |
|                                        | 6. Installation of plates between columns               |                                                 |
|                                        | 7. Installation of next-tire drop panels               |                                                 |
|                                        | 8. Installation of a telescopic strut under each       |                                                 |
|                                        | installed drop panel                                   |                                                 |
|                                        | 9. Installation of next-tire plates between columns     |                                                 |
|                                        | 10. Installation of middle plates                       |                                                 |
|                                        | 11. Concreting junctions between plates                 |                                                 |
|                                        | 12. Dismantling of conductors                          |                                                 |
|                                        | 13. Dismantling of support brackets                    |                                                 |

The analysis of the comparative characteristics provided in the table above shows that the suggested frame system with “concealed” girders is more technologically efficient.

4. Conclusions

The construction of buildings and facilities with flat slabs (smooth floors/ceilings) is possible with the use of flat-slab and beamless frame systems without column heads, as well as structural systems with “concealed” girders. Such buildings can be constructed using precast, precast/cast-in-situ and cast-in-situ technologies.

The analysis of the studies of foreign scientists focused on this topic shows that the main aspects of flat-slab construction are associated with the adoption of ready-to-use modular systems, which means precast technology is considered a preferred option. An exception is China leading the world by the number of the highest buildings, where the share of cast-in-situ construction exceeds 98%.
In consideration of the advantages and disadvantages of the more commonly used frame systems, a new structural system was developed for making precast/cast-in-situ frame buildings with flat slabs, differing from the existing systems by a new type coupling of structural elements, namely load-bearing columns and “concealed” girders, and a minimized effort in making the cast-in-situ part.

The suggested structural system differs from other systems by the following technological features characteristic of all frame systems using flat slabs: versatility of application, high performance capacity, rational design and technological intensity. The versatility of this technology is supported by the fact that columns are installed without the use of support brackets.

The new forming system meets the recent requirements for technology intensity, as it requires minimum labor input for installation and dismantling. It is also versatile, as it can be used for strengthening various structural elements (by way of their widening) and creating steel-concrete shells as part of building reconstruction. The forming system can be configured both as a three-dimensional closed P-structure and as a flat structure, depending on the purpose or type of a structural element to be strengthened and the work method.

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