Article

Stress State of Modular Blocks with Large Door Openings

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Abstract: Modular construction is a modern and efficient type of construction that has gained wide recognition in the construction industry. Limited research has been conducted on how large door openings affect the stress state of modular blocks. The present study aims to investigate the features of the stressed state of modular blocks with large door openings and the effect of size and place of the doors on the openings on the overall structural behavior of the building. Four full-scale (room-sized) modular blocks of the "lying cup" type were tested to failure under vertical loading with eccentricity simulating wind effects. The varied parameters of the specimens included concrete strength and the size of the window openings. Experimental results revealed that crack opening characteristics, main load-bearing wall deformations, horizontal deflections, and failure patterns under vertical loads are directly influenced by the small thickness and increased flexibility of the blocks. The effects of size and the placement of openings on the overall structural behavior of the building were analyzed. Tests revealed the distribution of compressive stresses in the main load-bearing walls of the "lying cup" blocks with an embedded reinforced concrete panel, considering vertical load eccentricity. Maximum compressive stresses in the longitudinal walls reached 70–80% of concrete strength, while in end walls and panel walls, they were 50–60%. Additionally, non-uniform deformations were observed in the supports of main load-bearing walls near the conjunction with the end walls and the edges of door openings. Average compressive strains in these walls were in the range of $470–500 \times 10^{-6}$, which corresponds to 22–29% of the cylindrical compressive strength of concrete. Partial factors accounting for loading conditions were introduced, allowing for further processing and the evaluation of the experimental data along with developing methods of analysis of buildings constructed with modular blocks.

Keywords: modular construction; structural analysis; large door openings; concrete strains; cracks; deflections; damage patterns

1. Introduction

Modular construction (MC) is a modern and efficient form of modular building that has gained significant recognition in the construction industry of the Commonwealth of independent state countries [1–3], Europe [4], Australia [5,6], and China [7,8]. Multi-level structures constructed using prefabricated reinforced concrete modules [9] are among the

most efficient modern construction types. Modular construction provides an accelerated solution to the housing problem by creating affordable housing for people. This method involves prefabricating modular blocks and then transferring them to the construction site for their erection into the complete structure.

Currently, nine modular-block construction plants are operating in Eurasian Economic Community countries: Prefab Technologies (Moscow) [10], MonArch (Moscow) [11], Evraz Steel House (Moscow/Moscow region) [12], OBD Vybor (Voronezh) [13], Krasnodar OBD (Krasnodar) [14], Technonicol House (Semenov, Nizhny Novgorod region) [15], Wood-Castor (Novosibirsk) [16], INPANS (St. Petersburg) [17], and ModeX (Astana) [18]. The leading products of these companies include modular facades, which are a structural system designed to arrange the facades of buildings and structures; plumbing modules, which are modular blocks of full factory readiness for sanitary facilities; and modular houses, which are standard modular structures of various parameters. In European countries, Max Bögl [19] is one of the leading construction companies in Germany, specializing in producing high-quality reinforced concrete modules. These modules are assembled from 2D panels and include modular structures such as engineering blocks and sanitary cabins.

The main advantages of modular blocks include a significant reduction in construction time, the transfer of basic construction processes to a factory environment, increased technical level and quality of construction, the automation of production, allowing for the use of efficient building materials, reduced impact of seasonal work, and significantly lower construction costs [5,20–23]. The disadvantages of modular-block housing construction include minimal experimental and theoretical research of such structural systems.

The structural advantages of modular block buildings are associated with a small wall thickness. In 2018, the ModeX LLP was launched in Astana, Kazakhstan. This plant produces reinforced concrete modular blocks of the "lying cup" type with an enlarged size [1]. These blocks are used to construct buildings, which are completed by placing them on top of each other, using a mortar layer as a base.

The inclusion of large door openings in modular blocks significantly influences the overall stressed state of the structure. Studies show that the presence of holes in the walls of modular units has a significant impact on their load-bearing capacity and stability. Researchers have investigated the stress states of door openings in modular blocks, recognizing their importance within structural mechanics [24,25]. This is particularly important when these blocks are subjected to external loads and internal modifications, such as the presence of large door openings or other openings. Kania T. et al. [26] have examined large door openings in structural elements by investigating cracking in ceramic partition walls with door openings using finite element methods (FEMs). Ali A. et al. [27] evaluated the effect of geometric shapes and the location of door opening configurations, showing that all specimens exhibit ductile flexural behavior at average drift ratios of 1%. Researchers [28] set out to find the practical shape of door frames by analyzing shear walls with different-shaped openings (rectangular, semicircular, and triangular) to determine their impact on load distribution. Lin Z-C has performed theoretical studies [29], used expert knowledge by analyzing the importance of technical and functional terms, and applied techniques for evaluating and improving the design of door-shaped structures. Guo et al. examined the impact of openings on the lateral stiffness and behavior of modular walls made of corrugated plates in high-rise buildings, revealing that the size and location of openings can significantly reduce the load-bearing capacity of structures under horizontal loads [30]. Liu and Crewe conducted a study on the effects of opening size and location on the load-bearing capacity of non-load-bearing masonry walls, showing that the improper placement of openings leads to stress concentration and a decrease in strength [31]. Chourasia et al. provided a comprehensive review of prefabricated volu-

metric modular construction systems, identifying key challenges and future development prospects of the technology [32]. Wang et al. investigated the seismic performance and load-bearing capacity of modular steel frames infilled with cold-formed steel walls with openings, demonstrating that the configuration of openings significantly affects the overall structural behavior under loads [33]. Additionally, the review by Ye et al. (2021) analyzes the stability issues of multi-story modular buildings, including the influence of joints and connections on the global stability of structures [34].

Despite significant progress in modular building construction, limited research has been conducted on how large door openings affect the stress state of modular blocks. This study aims to address this gap by experimentally investigating modular blocks with large door openings in the main load-bearing walls subjected to vertical force. Strain in the concrete of the main load-bearing walls was measured; crack formation and width were recorded, and horizontal deformations were determined based on the thickness of the walls to analyze damage accumulation and assess the failure mechanism. The results indicate that the stress state and premature failure of modular blocks are primarily influenced by their small wall thickness and increased flexibility. Furthermore, based on the experimental data from both this study and previous research [1], a relationship was established between the ultimate load of the modular block, which was caused by the loss of stability in the longitudinal walls, and the compressive stresses in the concrete walls, as well as the stresses in the vertical reinforcement.

These findings contribute to a better understanding of the structural behavior of modular blocks with large openings and provide a foundation for optimizing their design to enhance their overall stability and load-bearing capacity. This study is the first to investigate modular blocks with a 100 mm thick longitudinal wall, and further analysis requires additional planned research.

2. Materials and Methods

This study investigated specialized (non-standard) modular blocks of the "lying cup" type, with sizes of 7 (L) × 3.5 (B) × 3 (H) m, intended for use in the lower floors of high-rise buildings. The longitudinal walls of these modular blocks, which are 7 m long and 100 mm thick, had centrally located openings with different widths depending on the building height:

– Openings with a width of 4.2 m for buildings up to 9 stories;
– Openings with a width of 3.6 m for buildings up to 12 stories;
– Openings with a width of 3.0 m for buildings up to 17 stories.

For the production of modular blocks for standard floors, C20/25 concrete with a density of 1700 kg/m^3 was used (lightweight expanded clay concrete). For the 17-story buildings, the investigated blocks were made of C40/50 high-strength concrete. The manufacturing process followed the technology by using the molding machines, with the inclusion of opening formers and an increase in the workability of the concrete mix to ensure proper pre-forming of the floor. No additional post-treatment of the blocks was performed.

The blocks are reinforced with welded flat frames using 12 mm and 25 mm diameter bars (A500C) for wall supports, 16 mm diameter bars (A500C) for lintels, looped frames with 18 mm bars (A500C) at the long wall edges, and U-shaped horizontal reinforcement.

The thickness of the inserted load-bearing facade panel with an opening was varied between 120 mm and 160 mm. The "lying cup" block was formed as a five-plane structure and was later completed with an insertable load-bearing facade panel, which was secured by welding embedded parts and sealing the perimeter joint with a special high-strength mortar [1].

The testing of four modular blocks was conducted using a custom-designed testing facility. It consisted of a rigid spatial metal frame system with movable bearing elements. The tested modular block was placed on the top beam of the reinforced concrete frame, which incorporated beams supported by the lower beams of the stand. These beams were made of C20/25 concrete and specifically designed to support the weight of modular blocks within a three-dimensional model of a multi-story residential building (Figure 1).
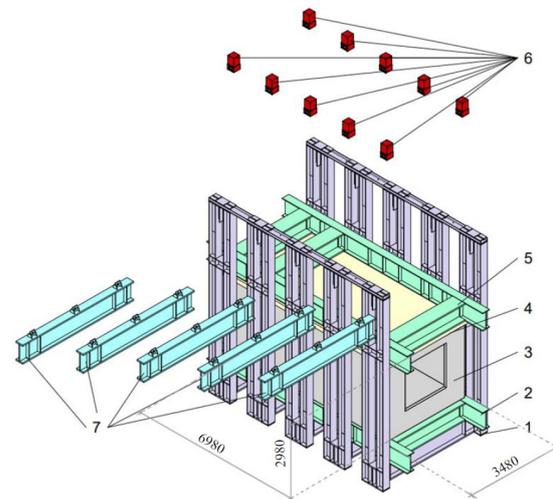
Figure 1. Schematic representation of the test facility with the installed modular block: (**1**) transverse power frame of the stand (5 pcs); (**2**) lower steel distribution frame; (**3**) the test specimen of the modular block; (**4**) distribution reinforced concrete slab; (**5**) upper steel distribution frame (lower support of hydraulic jacks); (**6**) 200 t hydraulic jacks (10 pcs); and (**7**) upper (lock) beams of power transverse frames (5 pcs.) and upper support of hydraulic jacks.

The adequacy of vertical reinforcement of the walls of the main load-bearing walls, which were made of centrally installed ribbed bars, was also examined. In addition, the reinforcement of the lintel beam above the opening in the longitudinal wall, which was reinforced with a flat welded frame, was studied. The ceiling and floor of the modular block were reinforced with triangular welded frames made of ribbed reinforcement bars with additional distribution meshes.

The loading of the modular block was performed using hydraulic jacks with a capacity of 200 tons each. The step-by-step load increase was monitored by measuring the pressure in the hydraulic system using pressure gauges. This created a uniform compressive load along the walls, applied with an eccentricity from 0.5 m to 0.75 m in the longitudinal direction of the specimen to simulate wind effects. Buildings of the volumetric modular system in the transverse direction (the most unfavorable in terms of the wind load) consist of two columns of modular blocks connected by a "brace" of the corridor slab. In this case, the eccentricity is defined as the ratio of the moment generated by the average (pressure and suction) wind load on the building façade for the wind region of Astana (according to EN) to the weight of the column of modules.

During testing, horizontal and vertical deflections at critical sections were recorded. Concrete compressive strains along the perimeter of the main load-bearing walls and within the compressed zone of the reinforced concrete column support beams were measured. The formation of cracks and the width of joint openings between the walls of the modular block and the inserted panel, as well as along the perimeter of the upper distribution slab, were recorded.

The fabrication of specimens, their curing, and testing were carried out in the main production facility of the operating ModeX plant.

To evaluate the strength of the modular block before testing, control specimens were prepared from the same concrete mix used for the block. These specimens included standard cubes (150 × 150 × 150 mm) and cylinders (150 × 300 mm), which were cured under identical conditions to the modular block. The compressive strength of concrete was determined using a hydraulic testing machine in accordance with EN 12390-3 [35].

The temperature was maintained at 18–20 °C, and the humidity ranged from 45 to 50%. The stability of these parameters was ensured by the plant's round-the-clock operation, with the primary source of heat and humidity being the molding section, where steam curing of the molding machines takes place.

The control of the step-by-step load increase was carried out by measuring the pressure in the hydraulic system using pressure gauges.

Strain gauges with a 50 mm base length and a division value of 10^{-5} were affixed to the concrete surfaces to monitor the strain distribution, complemented by the use of an AID-4M automatic data logger (Figures 2 and 3).
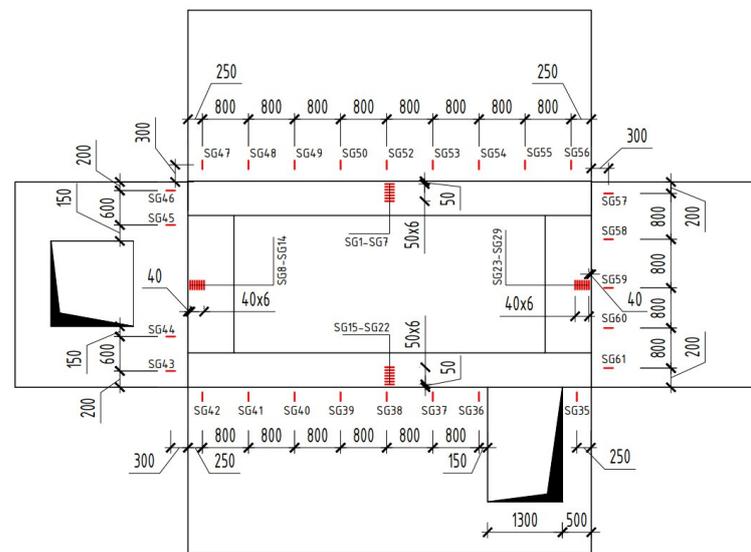
Figure 2. Scheme of the load strain gauge on the walls of the modular block.
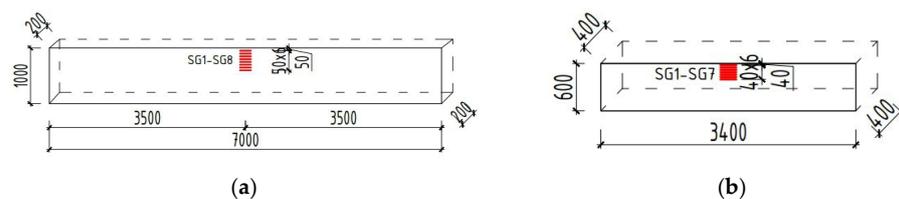

Figure 3. Arrangement of the strain gauge (**a**) on the longitudinal beams of the stylobate and (**b**) on the transverse beam of the column support beams.

Horizontal and vertical deflections were recorded using MG-4 and PAO-6 deflection measuring devices with a precision of 0.01 mm (Figure 4). The joint opening between the modular block and column support beams was assessed using PAO-6 deflectors with a resolution of 0.01 m. Additionally, an MPB-3 microscope, with a resolution of 0.02 μm, was employed to measure crack openings. The loading process was carried out incrementally, with each stage representing 5% to 7% of the anticipated maximum load. The design loads were determined based on the main combination of the design value of actions according to EN for a block with large openings, considering the loads from the upper tiers of standard volumetric blocks made of lightweight expanded clay concrete with a

density of 1700 kg/m^3 and taking into account the weight of all structures, live loads, and wind pressure.
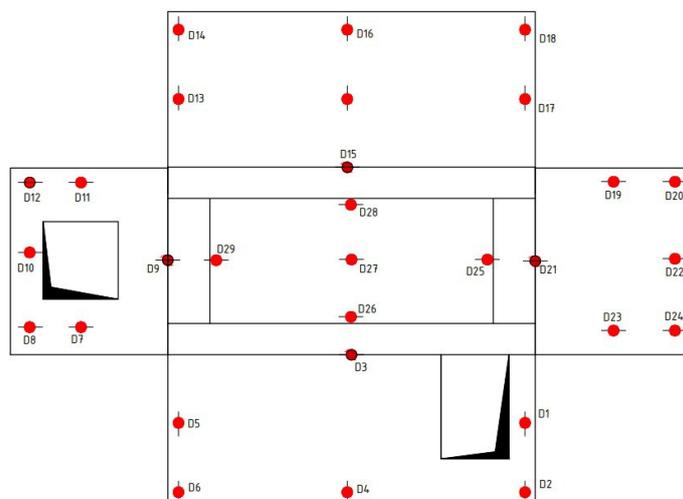

Figure 4. Scheme of the horizontal and vertical arrangement of the deflection indicator.

Figures 5 and 6 present a general view of the modular block test and the loading system section.
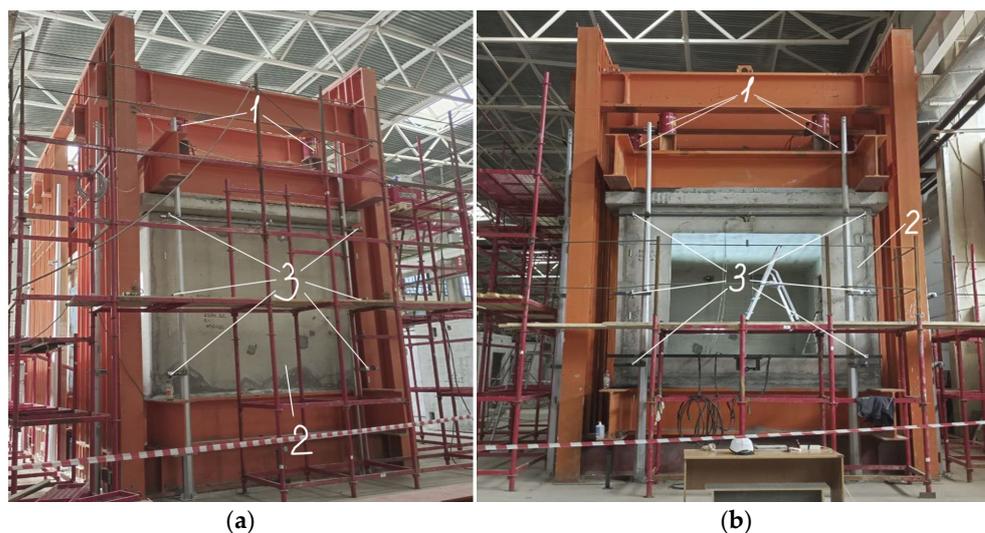

(**a**)	(**b**)

Figure 5. Layout of the tested specimen (**a**,**b**): (**1**) hydraulic jacks; (**2**) the modular unit under test; and (**3**) measuring devices.
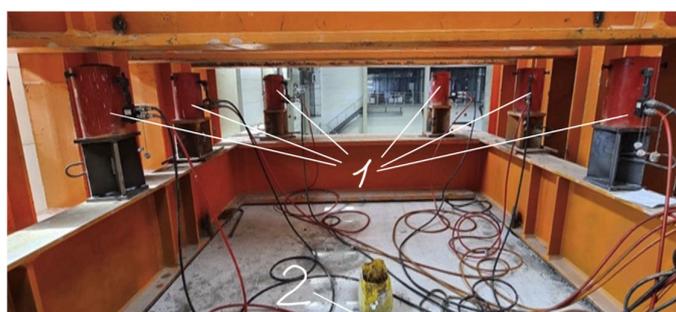
Figure 6. View of the loading system section (hydraulic jacks and beams of the power stand): (**1**) hydraulic jacks; (**2**) the modular unit tested.

Figures 7–9 show the setting of hydraulic jacks, strain gauges, and vertical and horizontal deflection measuring devices along the length of the walls to create a longitudinal force eccentricity of 0.75 m, thereby simulating the effects of wind.
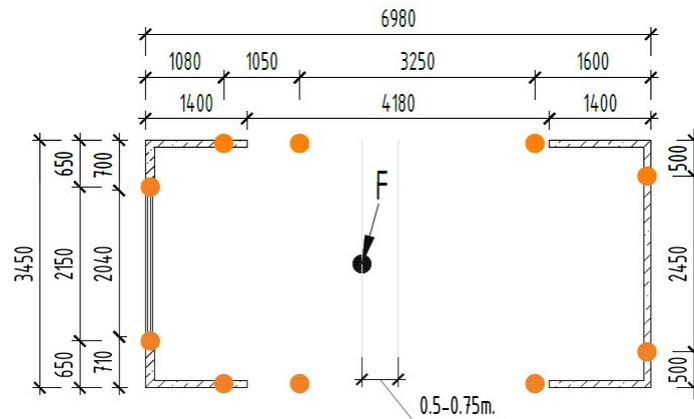

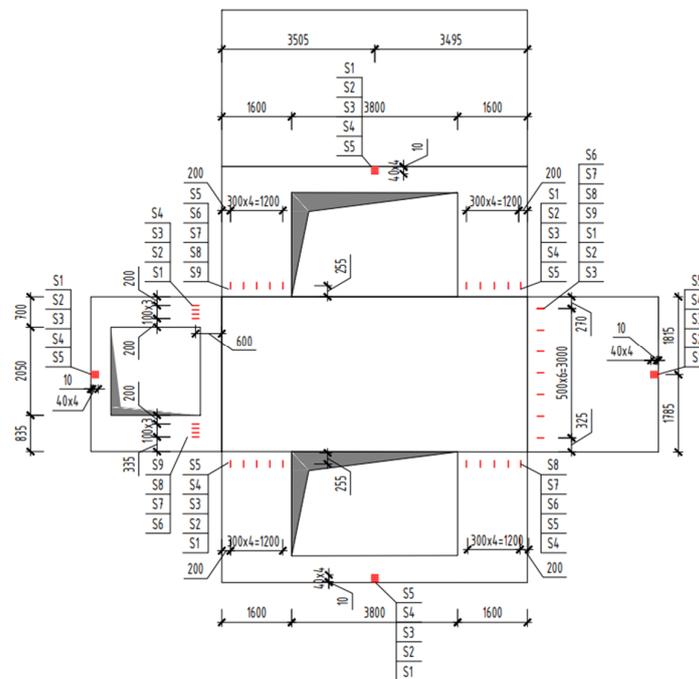**Figure 7.** Layout of the hydraulic jack, showing off-center loading of the modular block along the contour.

Figure 8. Position of the strain gauges.

The reinforced concrete beam in the frame floor were constructed using conventional C20/25 concrete and varied in strength and stiffness. The beams had rectangular cross-sections: in the first type, the main load-bearing beams had a cross-section of 200 × 1000 mm, and the cross-beams were 400 × 600 mm, while in the second type, the main load-bearing beams had a cross-section of 200 × 800 mm, and the cross-beams measured 200 × 500 mm. The beams are designed for the action of a vertical column, respectively, from modular modules of 16- and 12-story residential buildings. During the tests, a modular building block was subjected to vertical force from the overlying floors, applied using a group of 10 hydraulic jacks, each with a 200-tonne capacity. The stress state of the module's walls was carefully monitored throughout the testing process. The main criterion indicating the attainment of the ultimate load was the increase in deformations without a corresponding increase in load (a drop in pressure in the hydraulic jack system).

This is characteristic, as the thin-walled structure loses stability (local stability) after a certain accumulation of defects. Horizontal and vertical deflections at critical sections were recorded, along with measurements of concrete compressive strains along the perimeter of the modular block walls and across the height of the compressed concrete zone of the reinforced concrete column support beams. Additionally, crack widths and the opening of joints between the modular block walls and the frame floor beams were measured.
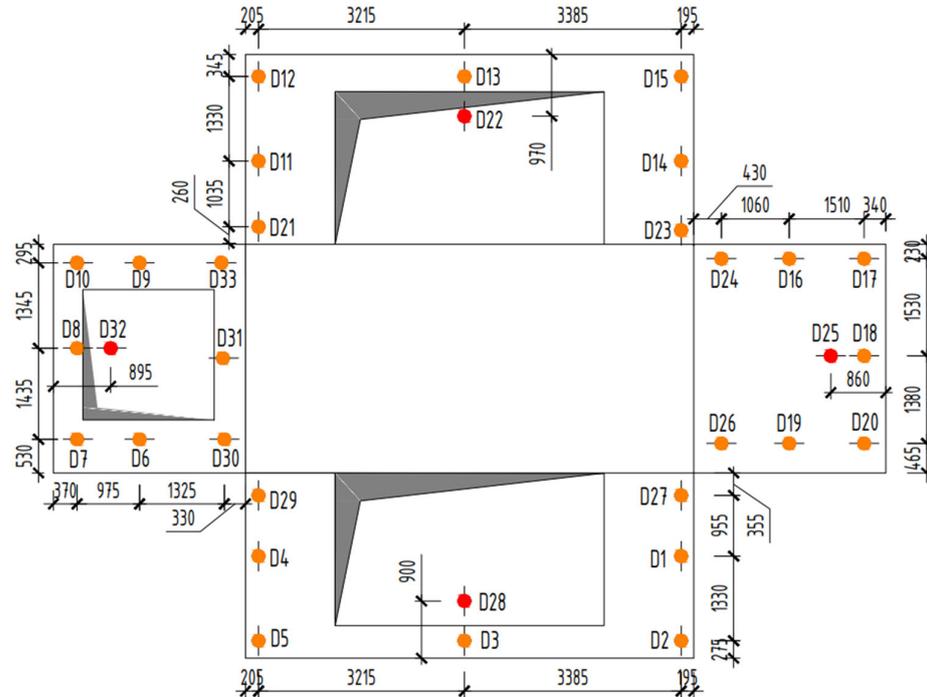
Figure 9. Layout of measuring devices for vertical displacement (red) and horizontal deflections (orange).

3. Results

3.1. Modular Block No. 1

The structural design of the building block is similar to that of lower-tier 9-story modular block structures. It is made from ordinary concrete C30/37. There is an enlarged opening with dimensions of 4180 × 2400 mm located in each main load-bearing wall, which is 100 mm thick. The end walls are also 100 mm thick and have no openings. The floor slab of the volume block has ribs, with a slab measuring 80 mm and ribs measuring 170 mm. The ceiling panel is flat, with a thickness of 80 mm to 97 mm. Reinforcement for the modular block is provided by spatial frames combined into a single unit (Figure 10).
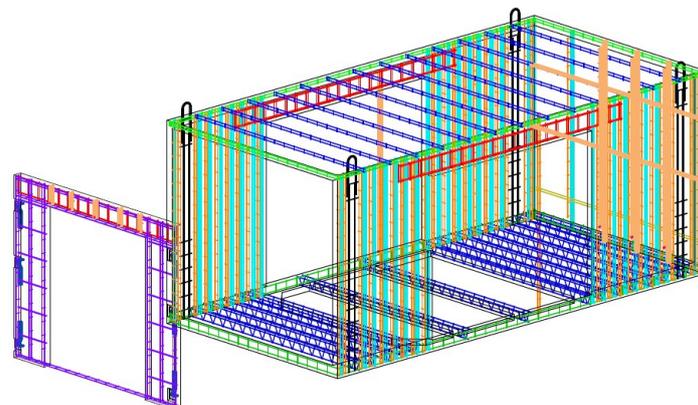

Figure 10. Reinforcement of the longitudinal and transverse walls.

Separate rods with a ribbed (periodic) profile and class A500 are used. An external (facade) single-layer wall panel is also used, measuring 120 mm, and a frame made from ordinary concrete C30/37 is also used. It has a window opening measuring 2050 × 2050 mm, as shown in Figure 11.
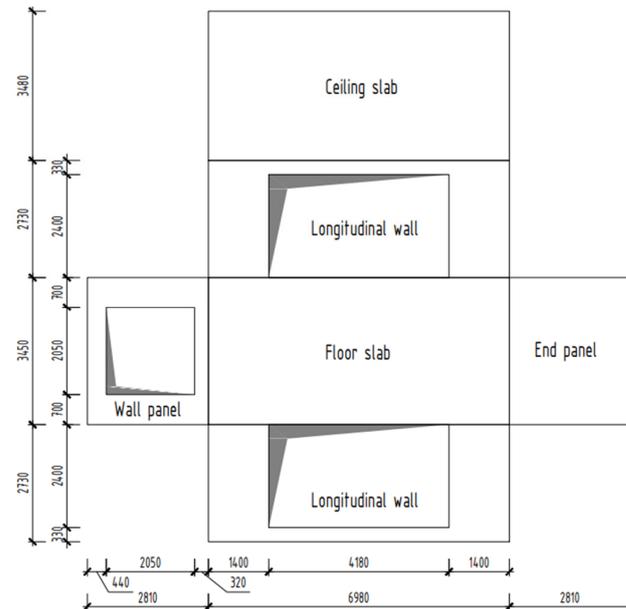

Figure 11. Layout of the modular block.

Before the tests, the cubic compressive strength of the concrete was measured within the range of 39–42 MPa, corresponding to concrete class C30/37. The measured width of transverse and longitudinal cracks did not exceed 0.5 mm except for a transverse crack on the ceiling panel with an opening of 0.4 cm.

The condition of the modular block was monitored during the loading process. Compressive strains, horizontal and vertical deflections, and crack opening widths were measured. Additionally, the general nature of any damage was also assessed, as shown in Figures 12 and 13.
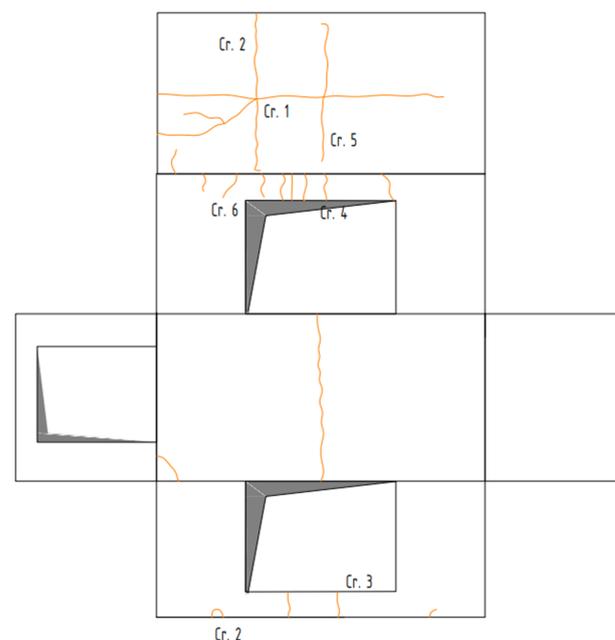

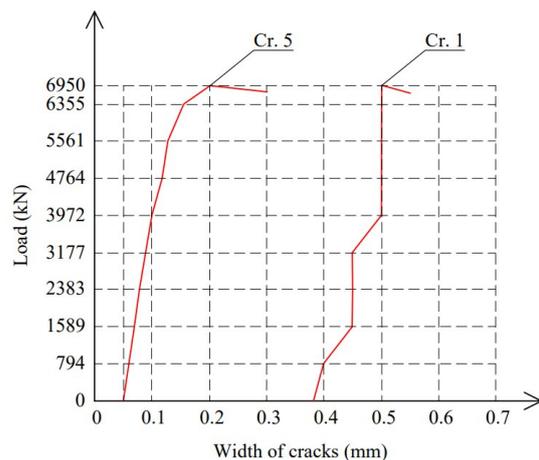**Figure 12.** Scheme of the cracks' location during the destruction of a modular block.

Figure 13. A graph of the development of transverse cracks (red) in the top panels.

Figures 14 and 15 show the diagrams of deflections of the walls from the plane of the modular block.
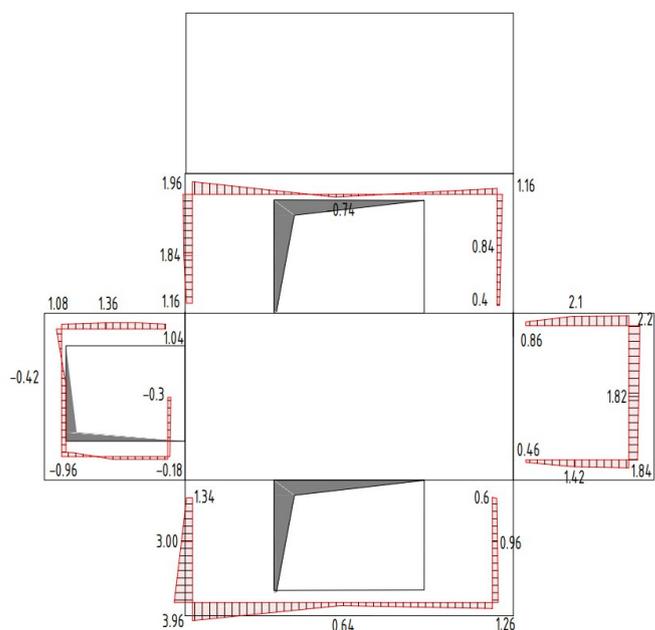

Figure 14. Scheme of horizontal wall deflections, mm in Block No. 1.
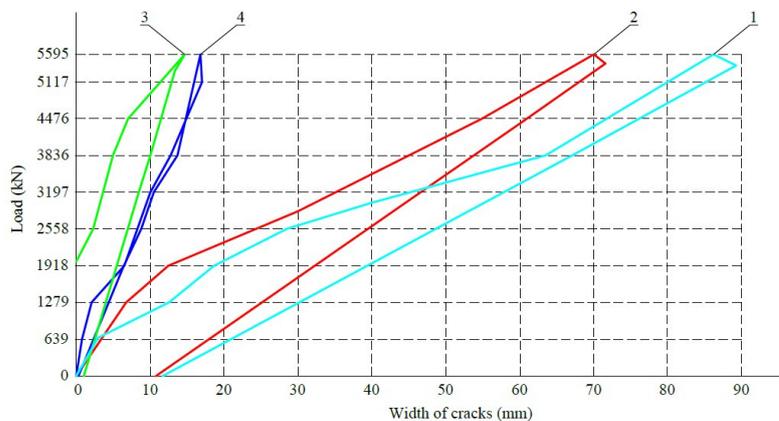

Figure 15. Diagram of horizontal wall deformations: (**1**, **2**) the main load-bearing walls; (**3**) end wall; and (**4**) wall panel.

Due to the significant force, vertical deflections of the span sections of the main load-bearing walls of the modular block were accompanied by increased concrete compressive strains in the middle part of the spans, as shown in Figure 16.
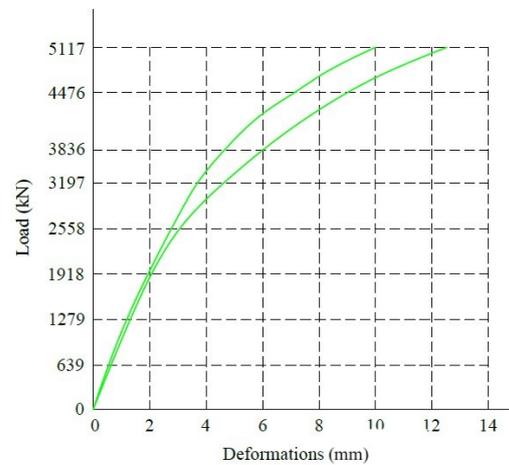

Figure 16. Diagram of strains in the compressed concrete zone of the main load-bearing walls.

Figures 17–19 illustrate the longitudinal strains of concrete along the perimeter and horizontal deformations of the modular block walls at different vertical force values.
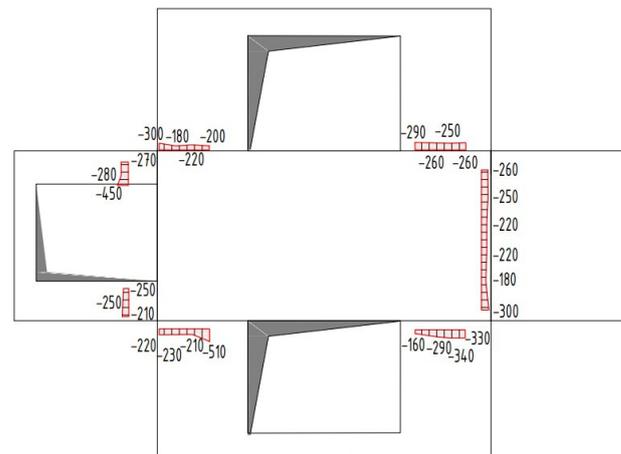

Figure 17. Scheme of concrete compressive strains, 10^{-6}, along the perimeter of the walls under a vertical force of N = 3197 kN.
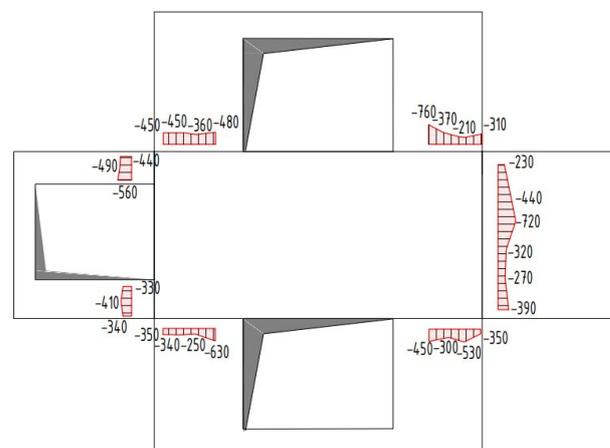

Figure 18. Scheme of concrete compressive strains, 10^{-6}, along the perimeter of the walls under a vertical force of N = 5114 kN.
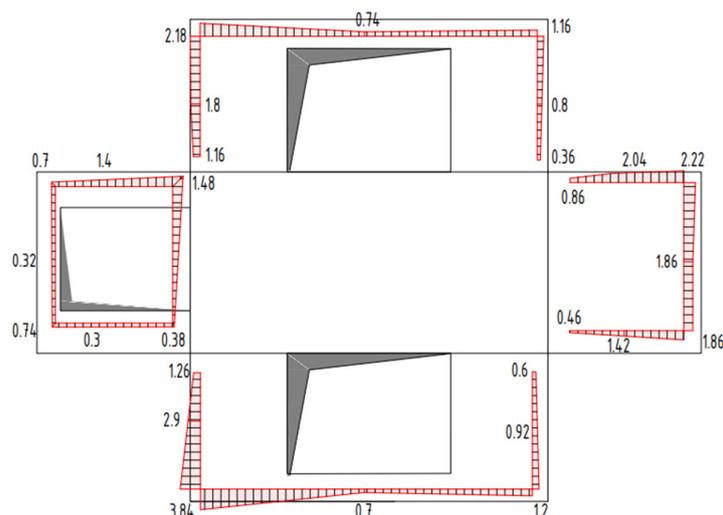
Figure 19. Horizontal deformations, mm, of the modular block walls under a vertical force of 5115 kN.

The primary damages to the modular block under the maximum load are shown in Figures 20 and 21.

Figure 20. Cracks in the ceiling panel and the lintel in the main load-bearing wall.

Figure 21. Fragment of the ceiling panel.

The cause of this type of failure in the thin-walled block with 4.2 m openings in the longitudinal walls was the redistribution of tensile forces to the lintels, ceiling, and floor of the modular block. In practical terms, this led to the necessity of installing additional longitudinal reinforcement in the floor, the effectiveness and sufficiency of which were confirmed during the testing of subsequent specimens.

The modular block failed at a load of N = 5594 kN and was accompanied by a fracture on the floor wall along a transverse crack, with an opening exceeding 2 mm, followed by the accelerated opening of transverse cracks in the coating plate and significant stress in the piers and lintels of the main load-bearing walls. The main criterion indicating the attainment of the ultimate load is the increase in deformations without a corresponding increase in load (a drop in pressure in the hydraulic jack system). The average compressive stresses in the concrete walls at a maximum load of 5115 kN was 5.27 MPa. The stresses at the extreme sections of the openings in the main load-bearing walls reached 8–10.5 MPa. This is characteristic because the thin-walled structure loses stability (local stability) after a certain accumulation of defects.

3.2. Modular Block No. 2

The structural design of the building follows the 14-story modular block structures. It is built using ordinary concrete C30/37. A large opening with dimensions of 3600 × 2400 mm is placed (installed) in each main load-bearing wall, with a thickness of 100 mm. The end walls, floors, and ceiling panels correspond to the first specimen. The modular blocks are reinforced with spatial reinforcement frames, compared to block No. 1. The external (facade) bearing single-layer wall panel, with a thickness of 120 mm, is also made from ordinary concrete C40/50. It has a window opening measuring 2050 × 2050 mm, similar to that of block No. 1 (Figure 11).

Prior to the testing of the model, a measurement was conducted to evaluate the strength of the test sample. The measured cube strength of the concrete was 52.9 MPa, with a density of 2300 kg/m^3, and it had a cylindrical strength of 33.9 MPa. Longitudinal compressive deformations were measured at 11×10^{-4}, while transverse deformations measured 2×10^{-4} (Figures 22 and 23). These samples were made from the same concrete used for molding the block and for monitoring the strength of the modular block.

Figure 22. Testing of a concrete cube and a concrete cylinder on an ALPHA 3-3000S hydraulic press.
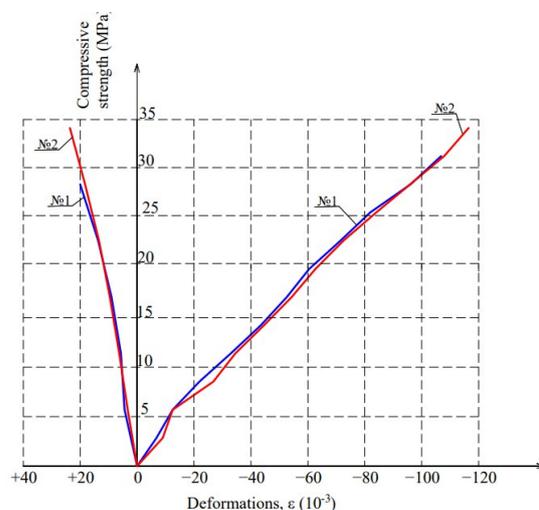

Figure 23. Diagram of longitudinal and transverse strains of concrete cylinders (No. 1, No. 2).

No significant defects or damage was found in the volume block elements, except for a transverse crack in the floor plate with a width of 0.3 mm and cracks in the lintels of the main load-bearing walls measuring 0.05 mm wide, as demonstrated in Figure 24.
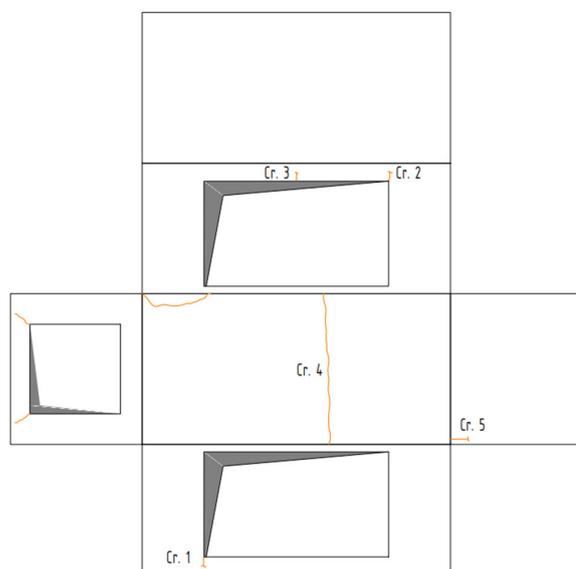

Figure 24. Cracks in the floor plate and lintels of the longitudinal and end walls in Block No. 2.

The hydraulic jacks were installed in accordance with the setup shown in Figure 7. The locations of load cells on the walls for measuring compressive deformations and installing deflection measuring devices were repeated as for the first specimen. Under a vertical force of N = 5754 kN and N = 6713 kN, amounting to 67% and 78%, respectively, of the maximum load, inclined cracks were observed in the end wall lintel, and the width of the crack in the floor slab was 0.4–0.5 cm. At a load of 7672 kN, corresponding to 89%, a crack formed in the angular part of the floor plate joint with the main load-bearing wall. Overall, the modular block was characterized by high crack resistance. Even after reaching the maximum load, the width of the transverse cracks in the floor did not exceed 0.6 cm, and the remaining cracks did not exceed 0.05–0.10 cm (Figure 25).
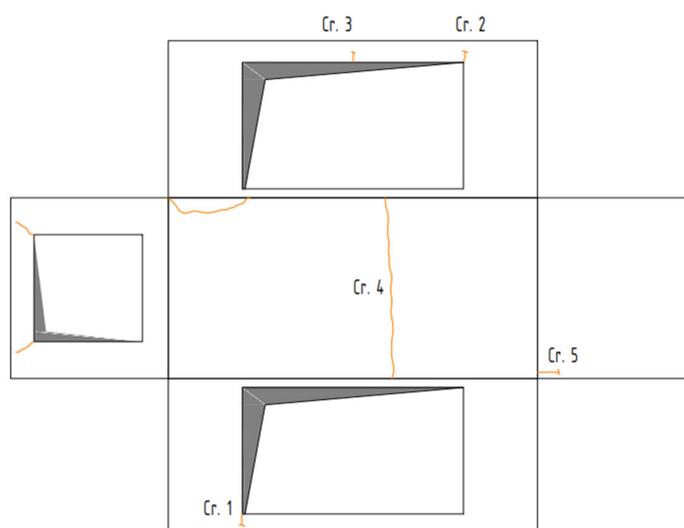

Figure 25. Scheme of the cracks at failure of a modular block.

Figure 26 shows the diagrams of horizontal deflections of walls from the plane of the modular block under a vertical force of N = 7672 kN. These diagrams indicate the beginning

of the loss of stability of the main load-bearing walls. This is confirmed by the excessive horizontal deviations of the upper part of the main load-bearing walls, which amount to 4.04 mm and 7.96 mm. The horizontal deflections of the wall panel also amount to 8.3 mm, while the horizontal deviations of the end wall do not exceed 2.0 mm.
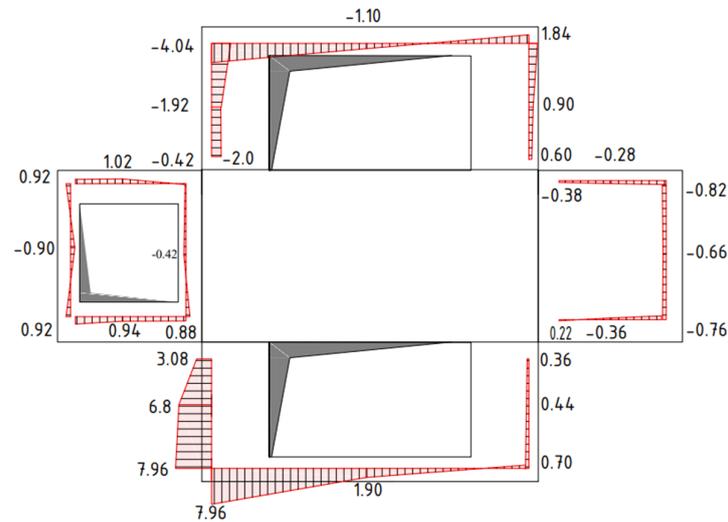

Figure 26. Scheme of horizontal wall deflections, mm in Block No. 2.

The vertical deflections of the span sections of the walls in a modular block, under a vertical force of N = 8311 kN, was 96% of the maximum load and ranged from 7.3 mm to 7.5 mm for the main load-bearing walls, 1.8 mm for the end wall, and 8.2 mm for the wall panel (Figure 27). The deflections in the end wall were approximately 4.1 to 4.6 times less than those in the main load-bearing walls and the wall panel.
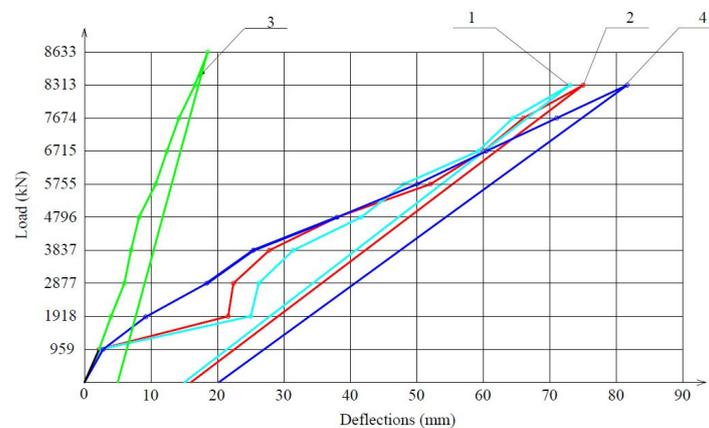

Figure 27. Diagram of horizontal wall deflections in mm: (**1**, **2**) the main load-bearing walls; (**3**) end wall; and (**4**) wall panel in Block No. 2.

The longitudinal (vertical) strains of the concrete along the perimeter of the walls of the modular block under a vertical force of N = 7672 kN were, on average, between (210 and 331) $\times$ 10^{-6}, with the end wall having a strain of 290 $\times$ 10^{-6} and the wall panel having a strain of 260 $\times$ 10^{-6} (Figure 28).

The destruction of the modular block occurred under a vertical force of 8631 kN and due to the loss of stability of the main load-bearing walls. The magnitude of horizontal deformations exceeded 7.3–8.2 cm from the plane of the walls, and the panel from the wall exceeded 0.6 cm. A transverse crack opened in the floor plate. Sample No. 2 was designed for use in the lower floor of a 14-story building, with a control load of N = 7839 kN. Failure occurred at 8631 kN, exceeding the control load by 9%. These loads simulate the conditions

of a first-floor module in a 14-story residential building, where the maximum design load reaches 7682 kN. The applied factor accounts for uncertainties in material properties, load variations, and long-term effects, ensuring the structural performance of the modular system under real-world conditions. However, the experimental vertical force on the block exceeded this design load by 9%, leading to its destruction. For the main combination of loads, the design impact value according to EN on a block with large openings from the 13 upper tiers of standard modular blocks made of lightweight aggregate concrete with a density of 1700 kg/m^3, considering the weight of all structures, live loads, and wind pressure, is 435.5 tons.
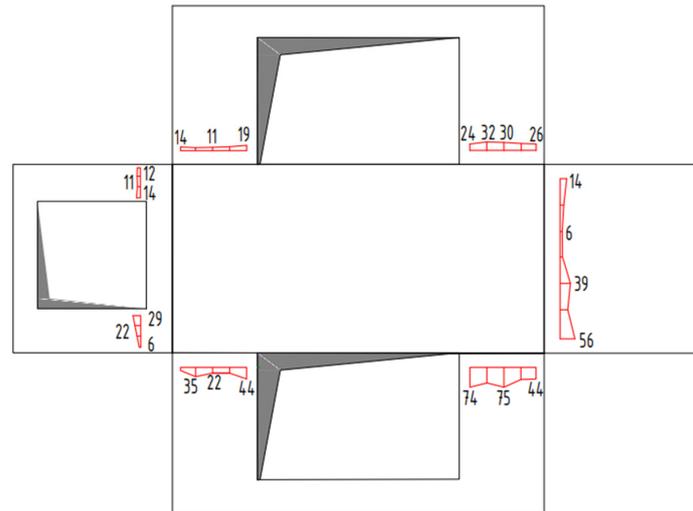

Figure 28. Scheme of concrete compressive strains, 10^{-6}, along the perimeter of walls under a vertical force of N = 7682 kN.

3.3. Modular Block No. 3

The structural design of the block is based on 16-story, modular building blocks. They are made of ordinary concrete C40/50. Each main load-bearing wall, measuring 100 mm in thickness, has a smaller opening compared to Block No. 2. The opening measures 3000 × 2400 mm. The end walls, floors, and ceiling panels correspond to the specifications of block No. 1. The modular blocks are reinforced with spatial reinforcement frames, which are thicker than those in blocks No. 1 and No. 2. The exterior, or façade, single-layer load-bearing wall panel in this specimen measures 160 mm thick and is made of heavy C30/40 concrete, with the same window openings as in previous designs in block No. 1. Figure 29 illustrates the geometric and cross-sectional characteristics of the reinforcement.
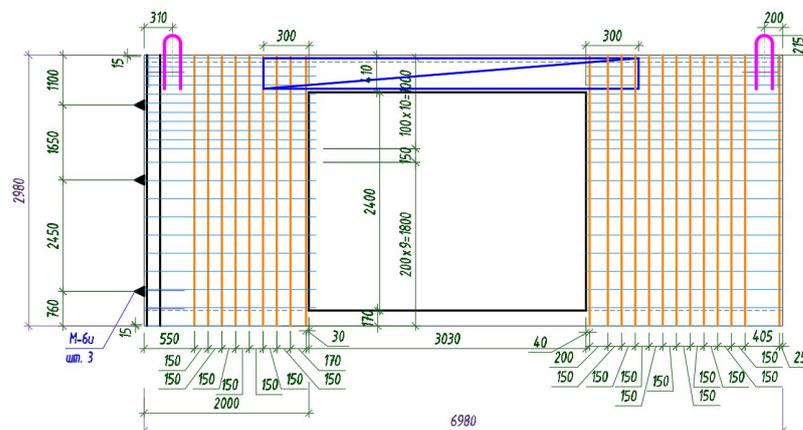

Figure 29. Reinforcement of the main load-bearing wall.

Before testing, the average strength of the concrete in a modular block was 45 MPa, with a density of 2120 kg/m^3 and a cylindrical strength of 35.9 MPa. The maximum longitudinal compressive strain of the concrete was 20.6×10^{-4}, and the maximum transverse deformation was 7×10^{-4}. The modulus of elasticity was 3×10^3 MPa, which indicates that the actual strength of the concrete corresponds to grade C35/45 according to the classification system.

The average cubic strength of the concrete in the wall panel was 43.7 MPa, with a cylindrical strength of 31.4 MPa. The maximum longitudinal compression strains of the concrete were 20.6×10^{-4}, and the maximum transverse deformations of the compressed concrete were 7×10^{-4}. The modulus of elasticity of the concrete was 3.0×10^{-4} MPa (Figures 30 and 31), which indicates that the actual concrete strength corresponds to grade C30/40 (B30). Longitudinal cracks were observed in the ceiling slab, with a crack width of 0.15–0.30 mm.
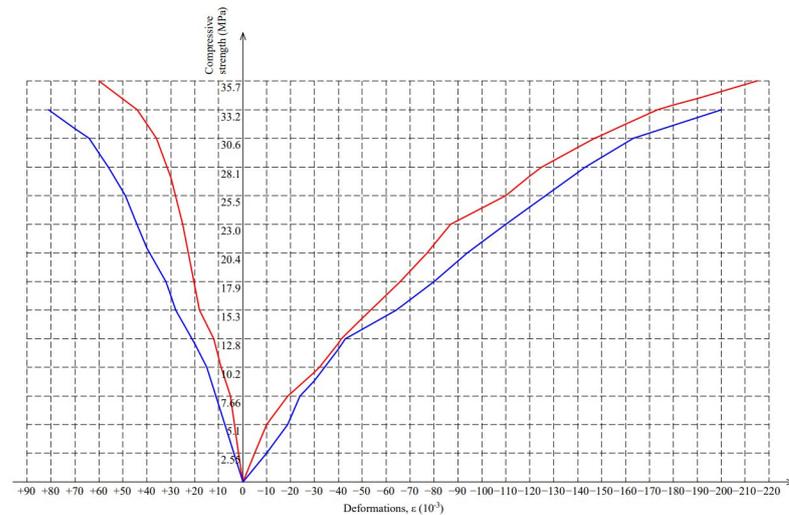
Figure 30. Diagram of longitudinal (red) and transverse (blue) strains of concrete cylinders of a modular block.

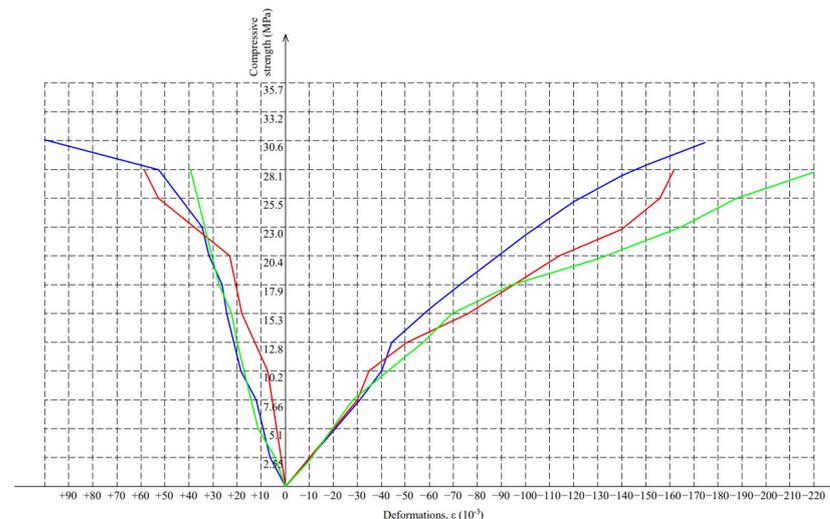**Figure 31.** Diagram of longitudinal (blue) and transverse (red, green) strains of concrete cylinders of the wall panel.

The examination of the modular block prior to the tests did not reveal any significant defects or damage. However, a transverse crack was detected in the floor slab, with an opening width of 0.25 mm, as illustrated in Figure 32. The sample's behavior is influenced

by the increased width of the wall piers in the longitudinal wall of the module. In these areas (at the specimens corners), the primary vertical force compresses.
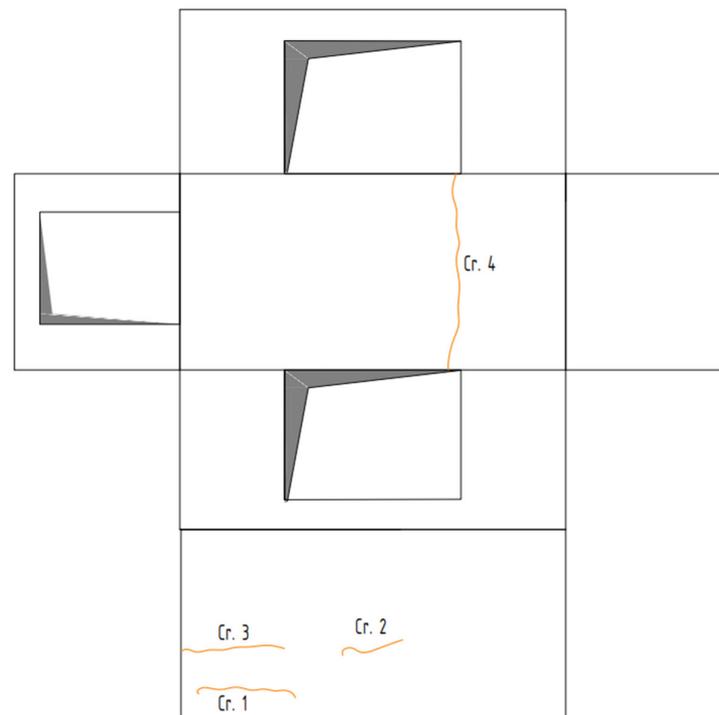

Figure 32. Cracks in the floor plate and lintels of the longitudinal and end walls in Block No. 3.

Hydraulic jacks were installed following block No. 1. The locations of the load cells on the walls for measuring compressive deformations and the installation of deflection measuring devices were the same as for the first specimen.

During the test, a vertical force of N = 195.7 kN was applied, which was 21% of the maximum possible load. As a result, normal cracks merged in the lintels of the main load-bearing walls, with an opening width of 0.25 mm. Under the same load, the longitudinal strains in the concrete of the walls ranged between $(4 \text{ and } 80) \times 10^{-6}$. In contrast, the horizontal deviations of the upper part of the main load-bearing walls varied between 0.24 mm and 1.22 mm, and the horizontal deflections of the wall panels ranged from 0.50 mm to 0.58 mm. The horizontal deviations of the end walls did not exceed 0.10 mm to 0.16 mm.

Under a vertical force of N = 3835 kN, corresponding to 42% of the maximum load, cracks were observed in the ceiling panel, with a width of 0.15–0.30 cm (Figure 33). At the same time, the concrete strains in the walls were between $(22 \text{ and } 770) \times 10^{-6}$, with an average of 360×10^{-6}. The horizontal deflections of the top of the main load-bearing walls ranged from 0.9 cm to 2.1 cm, and the horizontal deflections of the wall panels were between 0.5 mm and 0.9 mm. The deviations of the end walls ranged from 0.03 mm to 0.4 mm, while multiple cracks developed in the ceiling panel, reaching widths of up to 0.3 cm. Additionally, cracks formed in the lintels of the primary load-bearing walls, measuring between 0.05 cm and 0.2 cm in width, as shown in Figure 33.

Under a vertical force of N = 6713 kN, equivalent to 75% of the maximum possible force, the concrete in the walls experienced longitudinal strains ranging from $(220 \text{ to } 770) \times 10^{-6}$, with an average value of 360×10^{-6}. The horizontal deviations in the upper part of the walls varied from 1.48 cm to 3.62 cm, while the horizontal deflections in the wall panels were between 0.16 cm and 0.38 cm. The horizontal deflections of the end wall did not exceed 0.02–0.52 mm.
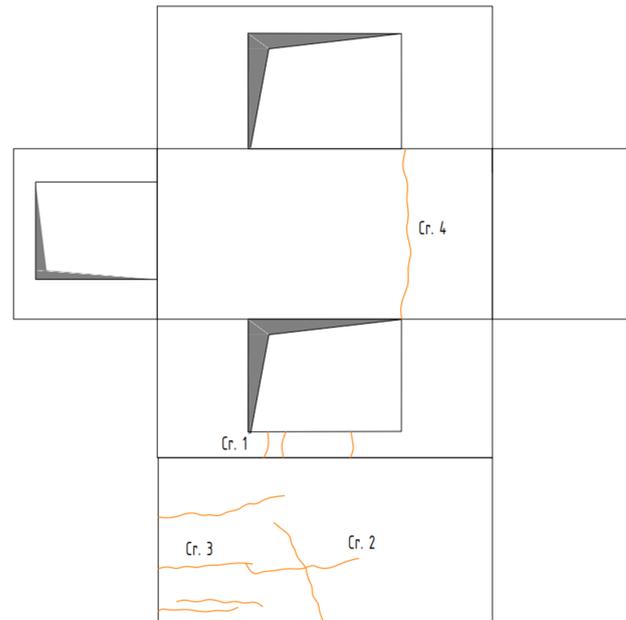
Figure 33. Scheme of cracks under a vertical force of N = 3835 kN.

With a load of N = 8631 kN applied vertically, which is equivalent to 96% of the maximum capacity, the concrete's longitudinal strains in the walls ranged between (290 and 900) $\times 10^{-6}$, with an average strain of 570×10^{-6}, as shown in Figure 34. The upper part of the main load-bearing wall experienced horizontal deviations between 3.68 mm and 3.82 mm.
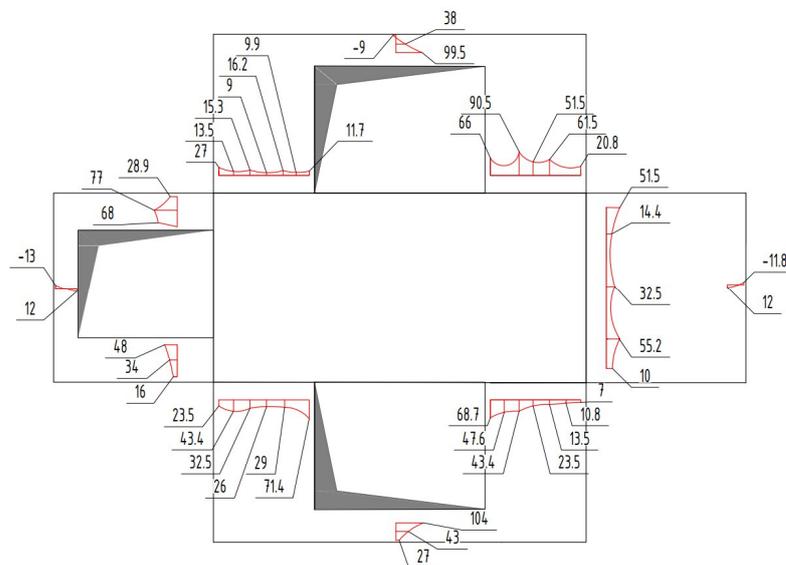
Figure 34. Diagram of concrete compressive strains along the perimeter of the walls under a vertical force of N = 8631 kN.

The horizontal deflections of the wall panels ranged from 1.26 mm to 2.0 mm, and the horizontal deviation of the end wall was between 0.14 mm and 0.26 mm (Figures 35 and 36).

The vertical deflections of the span sections of the walls of the volume block under a vertical force of 8631 kN, which is 96% of the maximum load, ranged between 7.3 mm and 7.5 mm for the main load-bearing walls, 1.8 mm for the end wall, and 8.2 mm for the wall panel (Figure 37). The vertical deflections of the end wall were about 4.1 to 4.6 times less than those of the main load-bearing wall and the wall panel.

Figure 35. Horizontal wall deflections at a vertical force of N = 8631 kN in mm.
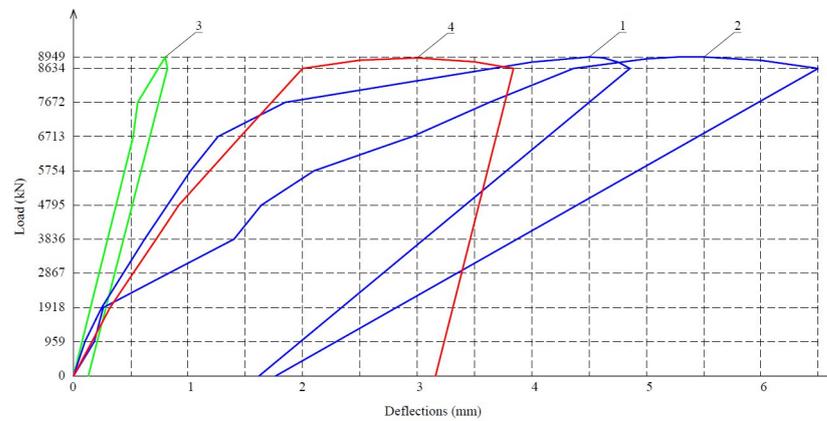
Figure 36. Diagram of horizontal wall deflections in mm: (**1**, **2**) the main load-bearing walls; (**3**) end wall; and (**4**) wall panel in Block No. 3.

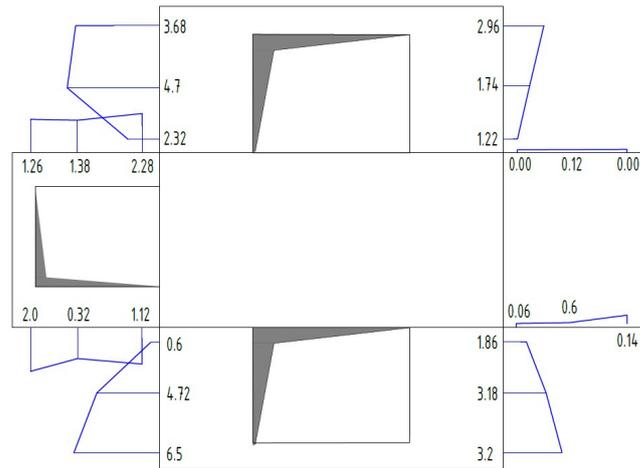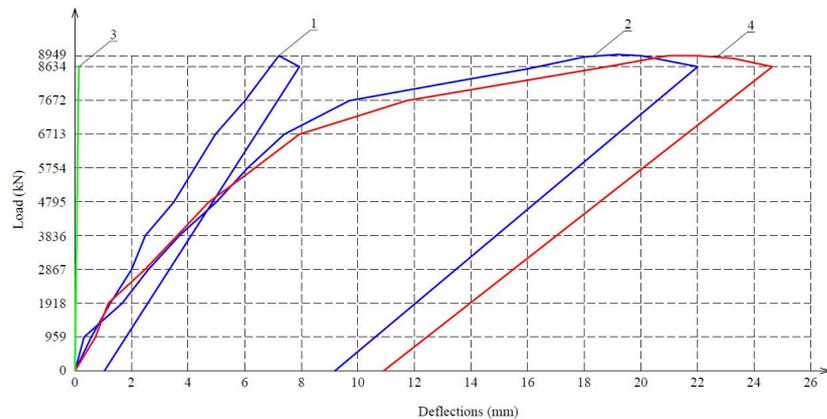**Figure 37.** Diagram of vertical deflections in mm: (**1**, **2**) the main load-bearing walls; (**3**) wall panel; and (**4**) end wall.

The lintels of the main load-bearing walls, during the initial stages of loading, functioned together with the lower part of the floor slab. As a result, the initial tensile strains in the concrete in the upper part of the lintels increased. However, as the vertical force increased, the lintels started to act as a T-shape structure formed by the floor slab and the lintel. This led to the tensile strains in the upper concrete of the lintels transforming into compressive deformations, reaching 1040×10^{-6} before the modular block failed. At the same time, the crack width in the lintels of the main load-bearing walls reached 0.40 cm, while in the ceiling panels, it extended up to 0.70 cm, as shown in Figure 38.

Figure 38. Diagram of cracks under a vertical force of N = 8631 kN.

The destruction of the modular block occurred under a vertical force of N = 8949 kN, leading to the collapse of the lintel and the main load-bearing wall. This was accompanied by a continuous increase in vertical wall deflection, horizontal displacement out of plane, and a significant crack opening. The greatest compressive stresses in the concrete reached 75% in the main load-bearing walls,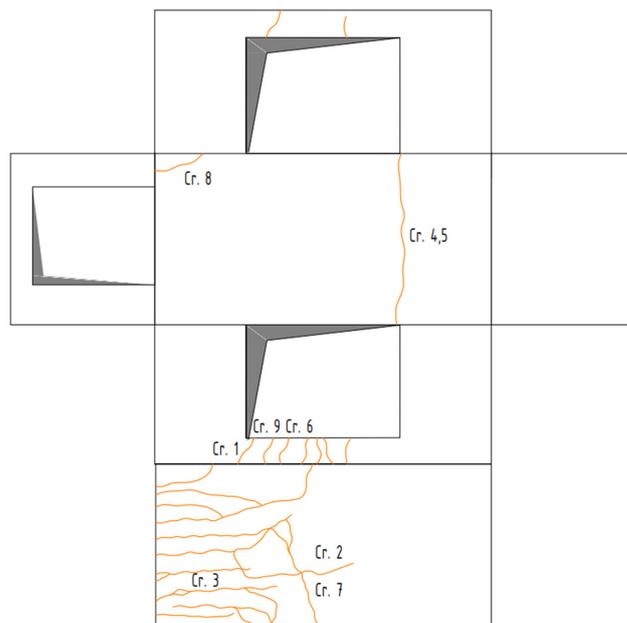 50% in the end wall, and 60% in the main load-bearing wall. The damage caused by the maximum load on the modular block is illustrated in Figures 39 and 40.

The specimen's behavior was associated with an increase in the width of the piers in the main load-bearing wall of the module. In these areas (at the corners of the specimen), the primary vertical compressive load from the upper structures was transmitted. As the opening size decreased, the junction of the lintel in the longitudinal wall shifted to a zone of higher tensile forces. This is due to the fact that during testing, to replicate the real behavior of the specimen as part of a multi-story building column, the load on the specimen's ceiling was transmitted through a distribution slab and a mortar joint with a strength of M200–M250. Up to a certain load level, the joint functioned with consideration of adhesion (friction) forces, as the mortar joint does not transfer the tensile force from the overlying structure.

Figure 39. Cracks in the lintel of the main load-bearing wall of the modular block.

The control vertical force on the modular block, with a safety factor of K = 1.8 corresponding to the first above-ground commercial floor of a 16-story residential building, was 10,350 kN. The experimental vertical force applied to the modular block was 12% less than the control load. Considering that the actual concrete strength of the experimental block is the same as C35/45 concrete, we can expect the vertical force to be at least equal to the reference load if the design strength is C40/50.

Figure 40. Damage to the lintel of the main load-bearing wall of the modular block.

3.4. Modular Block No. 4

Experimental block No. 4, designed for buildings up to 16 stories tall, was similar to the previously tested block No. 3, but it was made from more durable, ordinary concrete C40/50.

Under a vertical force of 10,547 kN, the formation of longitudinal and transverse cracks was observed in the ceiling panel. The cracks had an opening width of 0.05 to 0.1 mm. Simultaneously, the longitudinal strains in the concrete in the walls were between $(200 \text{ and } 400) \times 10^{-6}$. Peak strains in the main load-bearing walls ranged from 1130×10^{-6} to 2020×10^{-6}. Horizontal deformations of the upper part of the longitudinal and end walls ranged from 3.34 cm to 4.14 cm, and the horizontal displacement of the wall panel ranged from 0.34 cm to 0.58 cm (Figure 41).
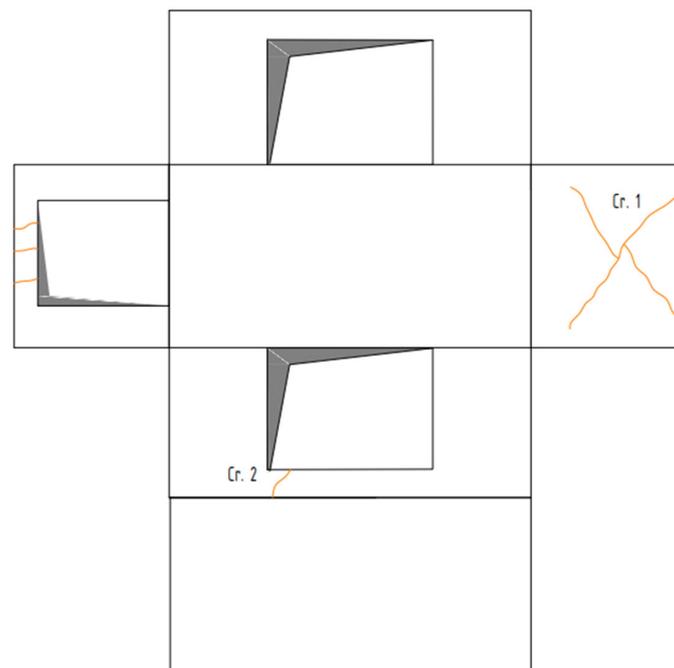

Figure 41. Diagram of the location of cracks under a vertical force of N = 10,545 kN.

Under a vertical force of 12,782 kN, new cracks appeared. The width of the existing cracks remained unchanged, but the longitudinal strains of the concrete in the walls ranged from 58×10^{-6} to 810×10^{-6}, with an average of 420×10^{-6}. The horizontal deviations of the upper part of the walls were between 3.88 cm and 4.94 cm, and the horizontal movements of the wall panels were between 0.52 cm and 1.09 cm. The most significant horizontal deviation of the end wall was 5.76 cm (Figures 42 and 43).
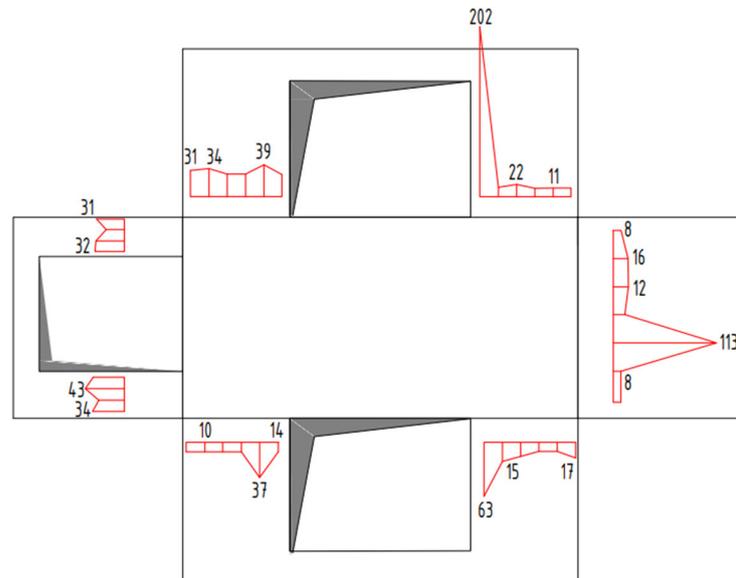
Figure 42. Scheme of compressive strains of concrete along, 10^{-6}, the perimeter of the walls under a vertical force of N = 12,782 kN.
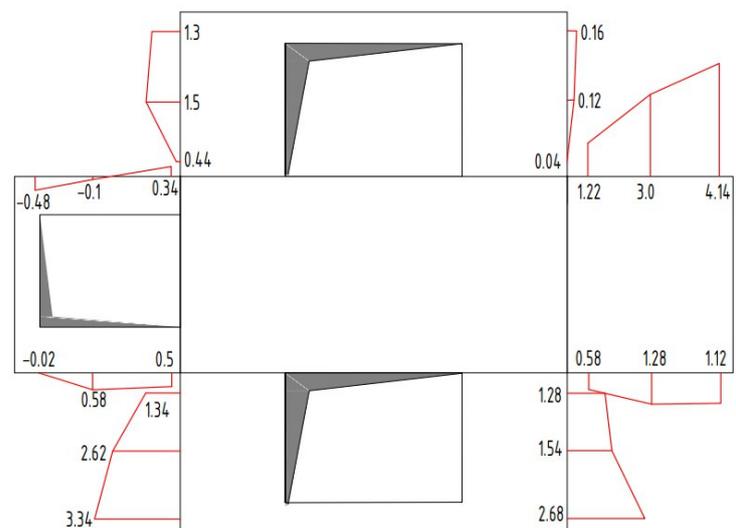
Figure 43. Horizontal wall deflections in mm at a vertical force of N = 12, 782 kN.

The vertical deflections of the wall lintels and the end wall of the modular block under a vertical force of N = 1304.33 kN were 9.18 and 10.4 mm, respectively, in the main load-bearing walls, 3.58 mm in the end wall, and 5.68 m in the wall panel, considering the deflection meter readings at zero pressure in the system after the failure load (Figure 44).

The cracks width in the lintels of the main load-bearing walls were 0.05–0.10 mm, and in the ceiling panel, they were 0.10–0.20 m, while in the end wall, they were 0.1 m, taking into account the readings of the deflection meters at zero pressure in the system after the failure load (Figure 45).
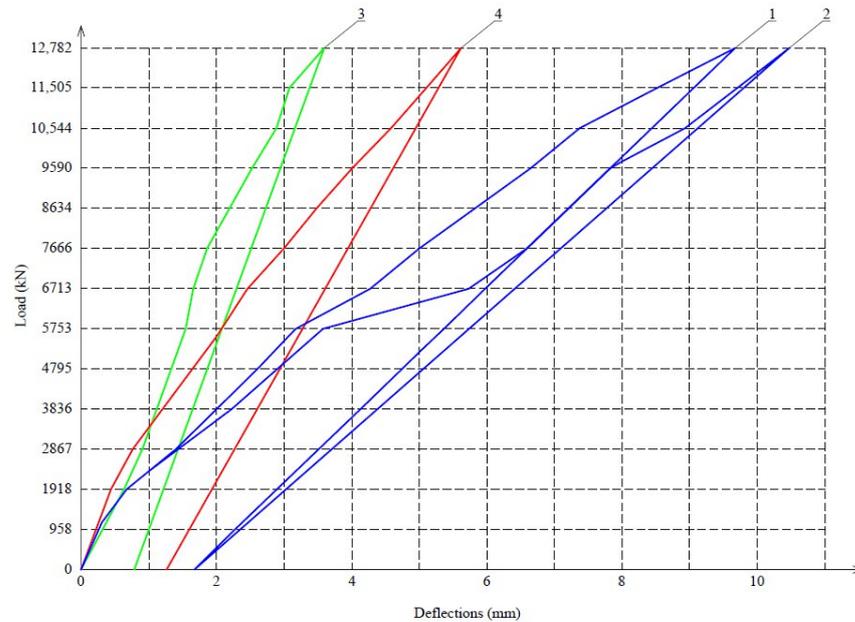
Figure 44. Diagram of horizontal wall deflections under a vertical force of N = 12,782 kN: (**1**, **2**) lintel deflections of the main load-bearing walls; (**3**) deflection of the lintel of the wall panel; and (**4**) deflections of the end wall.
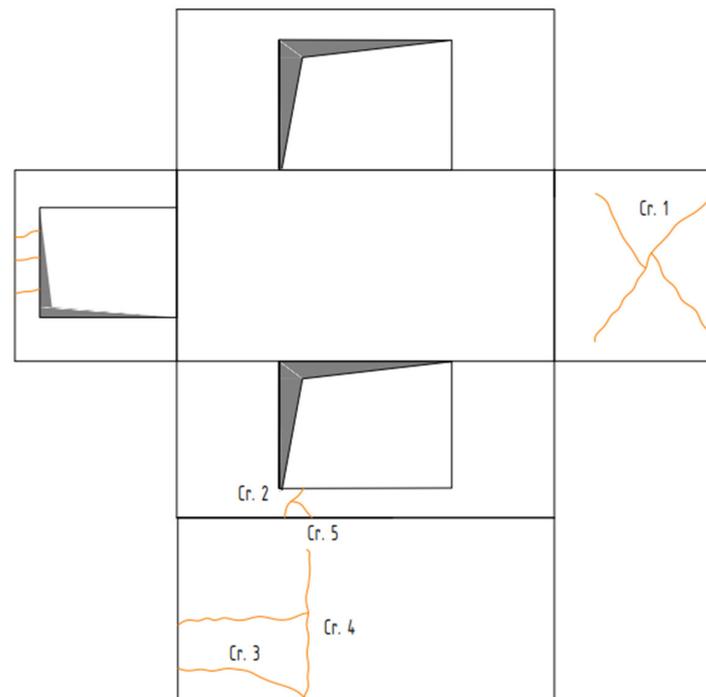
Figure 45. Diagram of the location of cracks under a vertical force of N = 12,782 kN.

At the initial stages of loading with a vertical force, the lintels of the main load-bearing walls worked in conjunction with the lower part of the floor slab, causing the initial strains in the concrete of the upper part to be tensile. However, as the vertical force increased, the lintels began to function as a T-shaped section formed by the floor slab and lintel, resulting in the tensile deformations of the upper part converting into compressive deformations. Under a vertical force of 12,782 kN, these compressive deformations reached a value of 1040×10^{-6}. The load was removed after reaching the control values for safety reasons, as no measures were in place in case of specimen collapse. The block was

brought to failure for analysis of its failure mechanism only after the necessary safety precautions were implemented.

After applying a vertical force of N = 12,782 kN, the tests were paused and continued after 35 days. During this time, the strain on the concrete in the elements of the modular block increased by an average of 2%. A further increase in the vertical force did not cause an increase in the width of existing cracks, except for a transverse crack in the floor plate and ceiling panel, where the crack width reached 1.30 cm and 0.55 cm, respectively. The destruction of the modular block failed at the load of N = 16,620 kN, followed by a continuous widening of transverse cracks that led to the separation of the panels (Figure 46).

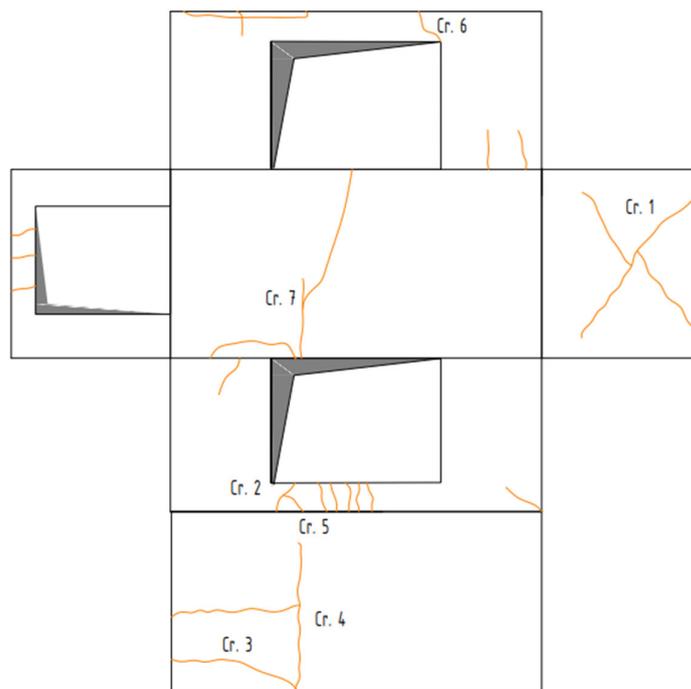**Figure 46.** Crack pattern under the maximum load.

A commercial modular block's experimental destructive vertical force was 66% higher than the control vertical force. At the same time, the failure load exceeded the control force of 12,092 kN by 66%.

Comparing the results of testing four modular blocks with previous studies, it can be noted that, in terms of strength and load-bearing capacity analysis, the tests conducted by Ryazhskikh B.E. demonstrated that a reinforced concrete modular block for a 17-story building had a load-bearing capacity exceeding the design load by 3.6 times [36]. In our tests, blocks No. 3 and No. 4, which were intended for high-rise buildings, showed a high margin of strength, withstanding loads exceeding the control values. This confirms the significant strength reserve of modular blocks, indicating the reliability of modular construction technology.

In studies on crack resistance and deformations, Tamov M.M. noted that during tests, the crack width and wall deformations of the block met regulatory requirements [37]. In our tests, especially on blocks No. 3 and No. 4, the formation of cracks was observed at loads ranging from 21% to 42% of the ultimate load. However, even under loads close to the ultimate, the crack width remained within permissible limits, which is consistent with the findings of previous studies.

Regarding structural design influences, in our tests, blocks with larger openings (e.g., block No. 1) demonstrated earlier crack formation and greater deformations com-

pared to blocks with smaller openings (e.g., block No. 3). This indicates the need for the careful design of openings to ensure the optimal stiffness and strength of the structure.

The study by Abramyan S.G. and co-authors discusses various structural schemes of rapidly erected buildings made of modular block modules [38]. Our results confirm that the use of reinforced reinforcement cages and high-strength concrete, as in blocks No. 3 and No. 4, improves the load-bearing capacity and crack resistance of the modules, which is in line with the conclusions made by these authors.

3.5. Structural Behavior Coefficient for Modular Blocks with Large Openings

The thickness of the ribbed vertical walls in the modular units described in this article and in study [1] is 70 mm for the caisson panels and 100 mm for the ribs. This structural system differs from the requirements of SP RK EN 1992-1-1:2014/211, which specifies a minimum thickness of 200 mm for load-bearing walls. Thus, we are dealing with a thin-walled structure, which is a system with increased flexibility.

A key challenge in the production of modular blocks is technological damage, primarily cracks that develop during manufacturing and further expand during transportation, installation, and under vertical loads from upper floors. The formation of these cracks, particularly at the junctions of walls and floor slabs, further reduces the stiffness of these connections and increases wall flexibility.

Based on experimental data from the testing of modular blocks (part of which is presented in this study and in [1]), failure occurs under vertical loading due to the loss of stability in longitudinal walls. This occurs when compressive stresses in the concrete walls reach 34–45% of the concrete strength and when stresses in the vertical reinforcement reach 20% of its design strength.

We have attempted to generalize the obtained results and performed calculations for the tested specimens to determine the permissible load based on the averaged compressive strength of the walls. This was performed by incorporating empirically derived partial coefficients for the working conditions of concrete and reinforcement.

The design strength of the concrete block $f_{cd.block}$ was determined by dividing the characteristic concrete strength by partial safety factors and by the experimentally determined partial coefficient of concrete working conditions in the walls of the modular block, $\gamma_{c.block}$, which varies depending on the type of concrete and the size of the openings in the block. The design strength of reinforcement $f_{yd.block}$ was also determined by dividing the characteristic strength by the safety factor and by the working condition coefficient for reinforcement in the walls of the modular block, $\gamma_{s.block}$, which was experimentally determined to be 10.

For each tested specimen, the horizontal cross-sectional area of the concrete walls, A_c, m^2 (excluding openings) and the area of the vertical reinforcement A_s, in m^2, were calculated. The averaged load-bearing capacity of the reinforced concrete walls of the modular block N while accounting for the combined work of concrete and reinforcement was determined using the following formula:

$$N = A_c \cdot f_{cd} + A_s \cdot f_{cd} \tag{1}$$

where N is the load-bearing capacity of the reinforced concrete walls, kN; A_c is the horizontal cross-sectional area of the concrete walls, in m^2; A_s is the area of the vertical reinforcement; and f_{cd} is the designed compressive strength of the concrete in a modular block, in kN/m.

The obtained calculated value N was then compared with the experimental strength of the modular blocks. The application of the partial behavior coefficients derived in this study for calculating the averaged wall strength showed a convergence of 11%. This deviation can

be reduced through further refinement with the accumulation and processing of additional experimental data.

Based on previous studies of modular blocks with door openings up to b = 1.3 m, we established the partial behavior coefficient for vertical loads caused by the increased flexibility of load-bearing walls:

– $\gamma_{c.block.lc}$ = 3.2 for lightweight concrete and expanded clay concrete with a density of 1800 kg/m^3;

– $\gamma_{c.block.hc}$ = 2.3 for heavy concrete.

In cases where the lower tier of modular blocks rests on beams of a flexible frame floor, the coefficient for concrete working conditions should be multiplied by an additional coefficient, $\gamma_{c.block}$. This accounts for the reduction in the strength of modular blocks compared to direct support on walls or foundations, which is caused by joint opening between the modular unit and the frame beams and a reduction in the support areas of longitudinal walls:

– $\gamma_{c.block.lc}$ = 3.1 for lightweight concrete and expanded clay concrete with a density of 1800 kg/m^3;

– $\gamma_{c.block.hc}$ = 2.8 for heavy concrete.

Table 1 presents data from this study on the partial behavior coefficient values for commercial modular blocks made of heavy concrete, with door openings ranging from 3.0 m to 4.2 m (Figure 47).

Table 1. Strength of commercial blocks.

№ of Block	The Width of the Doorway, m	Type of Main Load-Bearing Walls t, mm	Load Bearing Capacity N, tf	Concrete Strength, MPa	Partial Coefficient of Behavior $\gamma_{c \cdot hc}$
1	4.2	100 mm	594.7	C30/42	$\gamma_{c \cdot hc}$ = 4.05
2	3.6	100 mm	904.47	C34/52.9	$\gamma_{c \cdot hc}$ = 3.08
3	3.0	100 mm	937	fine-grained C35/45	$\gamma_{c \cdot hc}$ = 2.5
4	3.0	100 mm	1328.53	fine-grained C40/53	$\gamma_{c \cdot hc}$ = 2.0

Additional reinforcement of the wall piers in the longitudinal walls with Ø18 S500C vertical reinforcement, installed at a spacing of 70 mm, resulted in a 0.5 reduction in the partial coefficient of stability loss for modular blocks made of heavy concrete in this experiment.
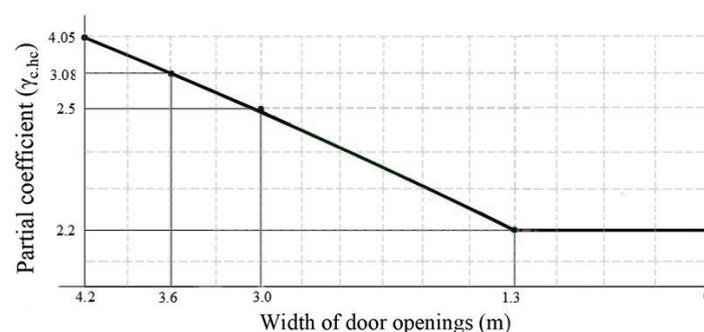
Figure 47. Dependence of the modular block performance ratio on the width of door openings.

The results of the studies presented in this article allow for determining the value of the partial behavior coefficient of modular blocks with increased door opening widths under vertical force, which was caused by the increased flexibility of load-bearing walls, using the formula:

$$2.3 < \gamma_{c.block} = 2.3 + 0.65\,(a - 1.3) \leq 4.05 \tag{2}$$

The comparison of our results with previous studies confirms the efficiency and reliability of modular construction. The high strength performance, significant load-bearing

capacity reserves, and satisfactory crack resistance allow this technology to be recommended for the construction of high-rise buildings.

4. Conclusions

Multi-story buildings constructed from reinforced concrete modular blocks, sized as individual rooms, represent one of the most efficient modern construction methods. This approach significantly accelerates the construction process by shifting over 90% of the fabrication to controlled factory conditions, addressing the challenge of providing affordable housing. Contemporary architectural demands necessitate the creation of flats with flexible layouts on different levels of high-rise residential buildings, as well as the integration of shared spaces and open areas within the modular block structural system, particularly on lower floors.

In our previous study [1], we presented experimental tests of modular blocks installed on a flexible frame, allowing for an open layout on the lower floors. This system was successfully implemented in Astana. However, the transition to a column–beam system resulted in increased construction time. Within the broader strategy of advancing construction systems by increasing the level of prefabrication and reducing construction time, the introduction of modular blocks with large openings offers a promising solution. This is achieved through the use of thin-walled, monolithically formed elements, commonly referred to as "lying cup" structures.

The fulfilled experimental research revealed the dependence of the stress state of modular blocks on the size of door openings, establishing the sequence and width of crack formation in walls and slabs, the ultimate out-of-plane deformations of walls, the distribution of longitudinal deformations in concrete walls, and the failure patterns of modular blocks, which include the following:

- Concrete failure in longitudinal walls in the crack development zone at the junction of walls and slabs near the connection to the end wall;
- Separation of the modular block into individual elements;
- Formation of inclined cracks in the slab, leading to its detachment from the end wall;
- Failure of lintels in longitudinal walls.

In our research, an attempt was made to generalize the obtained results for the tested specimens. The introduction of specific working condition coefficients allows for a more systematic approach to process and evaluate future experimental data to refine these dependencies. At this stage, it is already possible to determine the approximate permissible load for modular blocks by calculating the averaged compressive strength of the walls, taking into account the specific working condition coefficients for both concrete and reinforcement. This serves as a preliminary step before conducting further tests prior to industrial implementation.

This study provides valuable insights into the structural behavior of modular blocks with large door openings under vertical loads. The findings contribute to a better understanding of how large door openings affect the stress state of modular structures, addressing a previously unexplored aspect of modular construction.

Author Contributions: Conceptualization, I.T. and Z.Z.; methodology, A.B.; software, T.Z.; validation, U.A. and A.T.; formal analysis, I.T. and A.T.; investigation, I.T.; resources, A.B.; data curation, T.Z.; writing—original draft preparation, A.T. and I.T.; writing—review and editing, M.T.; visualization, U.A.; supervision, A.B. and M.T.; project administration, Z.Z.; funding acquisition, I.T. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

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