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Orginal Article

Restoration of load-bearing structures in a multi-storey residential building after a fire caused by military operations

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Abstract: This article presents the visual and instrumental investigations, along with the necessary engineering and technical decisions, for restoring load-bearing structures of multi-storey residential buildings damaged by fire due to war. It is economically advisable to replace and strengthen 20% of the emergency floor slabs and 16% of the load-bearing walls to allow residents to return to their homes as soon as possible. The temperature during the fire was determined using specific samples of damaged materials, building structures, and equipment, which allowed for a more accurate assessment of the damage to brick walls and prefabricated reinforced concrete floor slabs. The possibility of further use of the building was also determined based on a survey and necessary measurements of its structures, including the determination of physical and mechanical characteristics (crack width, flexures, concrete strength, brick grade, and mortar grade). The prefabricated reinforced concrete round hollow floor slabs had delaminated along the ribs between the hollows, showing sagging. The bricks had changed colour and were destroyed to a depth of 120 mm (internal walls were destroyed to this depth on both sides). Considering the extent of the damage to the load-bearing structures, it is recommended that the inter-floor ceilings, load-bearing walls, and partitions be replaced and strengthened. For structures that do not require replacement or reinforcement, the justification for their continued safe operation has been completed in accordance with the construction standards and regulations in force in Ukraine.

Keywords: multi-storey residential building, prefabricated reinforced concrete floor slabs, cracks, fire loading, fire

1. Introduction

The visual and instrumental investigations enable us to assess the existing technical state of building structures and to determine the possibility of further use [17]. Various causes of damage reduce the durability of structures and sometimes render their continued use impossible [20,21]. It is essential to carry out field tests, analysing the behaviour of the structure under stressed and deformed conditions to select the best method of strengthening, considering material consumption and labour intensity [6,7,18].

Over the last two years, a war has been taking place in Ukraine, leading to the damage and destruction of many buildings and structures. In most cases, the buildings were not physically destroyed but were damaged by blast waves and fire loads. Different structures and materials react differently to fire, leading to a loss of load-bearing capacity. Unfortunately, designers and researchers have encountered challenges in restoring damaged structures. These challenges arise because there is limited research on the strengthening or restoration of buildings damaged by war. Most studies primarily concern the restoration of buildings that were damaged or destroyed during World War II, such as the restoration of buildings in rural settlements in Great Britain [4] or the restoration of buildings in Polish cities [14–16].

However, as a result of the conflicts and wars in the Balkans, Syria, Georgia, Iraq, and now the ongoing war that is devastating Ukrainian cities, scientists and designers are compelled to conduct new research to restore what has been destroyed or damaged by the enemy. Noteworthy and unique studies include those focused on the restoration of architectural monuments in Aleppo [3], the use of aerial photography to detect building damage [5], the restoration of buildings in Sarajevo [8], the use of recycled concrete aggregate from destroyed buildings in Syria [9], the restoration of urban infrastructure in Mosul (Iraq) [10], the development of strategies for the restoration of damaged buildings in cities [11], and the assessment of damage to buildings in Kyiv [12].

In this context, the damage analysis of the load-bearing structures was also informed by studies on prefabricated reinforced concrete structures of the frame of a sports rifle school building after a fire caused by deliberate arson [1], studies on the temperature development during fires in industrial buildings made of precast concrete [19], the determination of the technical condition of reinforced concrete structures after fire exposure [13], fire investigation methods [23–30], and an improved method for determining the temperature of structures to evaluate their fire resistance, with specific attention to the behaviour of composite steel-concrete slabs under fire conditions [2].

This scientific work aims to analyse the damaged load-bearing structures of a multi-storey residential building after exposure to an uncontrolled fire load, and to make decisions regarding the possibility of their continued use.

2. Materials and methods

The fire loading that caused significant defects and structural damage to the multi-storey residential building was a result of air strikes in Borodyanka, Kyiv region. The damaged residential building consisted of three sections and seven entrances.

The multi-storey residential building, which requires investigation and reinforcement after the fire, has a complex shape (Fig. 1). It is separated from the neighbouring five-storey sections by deformation joints. The first section, with three entrances, is adjacent to the 'A/1' axis. The third section, with two entrances, adjoins the 'A/2' axis.

Accordingly, the fourth entrance is located between axes '1' and '4', and the fifth entrance is between axes '4' and '7'. Entrances within the section are mirrored relative to axis '4'. The building consists of eight floors. The basement and service floors are accessible through two entrances within the entire building area. A restaurant is situated on the first floor of the residential building, with its entrance from the main facade along the 'C' axis. Two apartments are located on each of the upper floors, with access organized by stairwells between axes '2'–'3' and '5'–'6'. Entry to the entrances is provided from the yard side along the 'A' axis (Fig. 2). The roof is flat.

The first section is a five-storey building with three entrances. The second section is an eight-storey building with two entrances. The third section is a five-storey building with two entrances. The third section suffered direct damage from an aerial bomb, resulting in almost complete destruction, making restoration impossible. Additionally, the fire spread to the fifth entrance of the second eight-storey section (Figs 1, 2).

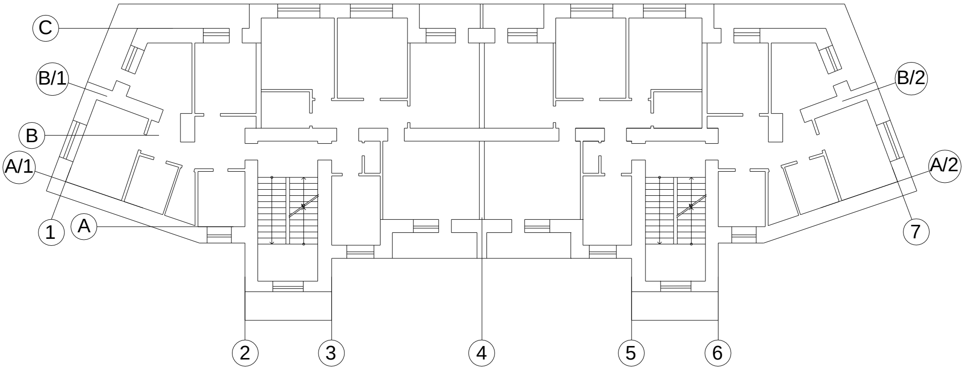

Fig. 1. The layout of an eight-storey section of a multi-storey residential building

Fig. 2. Facade facing the yard along axis ‘A’

The structural scheme of the eight-storey residential building is wall-mounted with longitudinal load-bearing brick walls (Fig. 1). The floor slabs and staircases are made of precast reinforced concrete. The walls of the building are constructed from thickened sand-lime bricks, with dimensions of 250 x 120 x 135 mm. The brick strength is M200, and the mortar strength is M75. The wall thickness on the first, second, and third floors is 640 mm, while from the fourth to the eighth floors, the thickness is 510 mm. The ceilings are made of prefabricated reinforced concrete round hollow floor slabs, and the lintels are also prefabricated reinforced concrete. The internal partitions within the apartments are made of gypsum plasterboard with a thickness of 100 mm. The inter-apartment partitions are double gypsum with a total thickness of 220 mm. The balconies and loggias consist of prefabricated reinforced concrete slabs. The foundations are pile-based. The spatial stability (rigidity) of the building is ensured by the longitudinal and transverse walls, as well as the floor slabs.

All load-bearing structures of the ceilings on each floor are made of prefabricated reinforced concrete round hollow floor slabs, with dimensions of 1.2 x 6.3 x 0.22 (h), 1.2 x 5 x 0.22 (h), and 1.2 x 4.5 x 0.22 (h). However, between axes '1'-'2' and '6'-'7', the direction of the floor slabs and load-bearing walls changes, and monolithic areas are arranged. The slabs rest on the longitudinal load-bearing walls, which are aligned with the lettered axes. The lintels in the load-bearing walls are made of prefabricated reinforced concrete with a minimum bearing depth of 250 mm.

The fire reached the apartments of the building due to the ignition of items on the balconies and loggias of the fifth entrance. The first, second, and third entrances of the five-storey section and the fourth entrance of the eight-storey section were damaged to varying degrees by the impact of the blast wave alone.

The fire load on the load-bearing structures of the fifth entrance of the eight-storey section resulted from the burning of residents' property in individual apartments, each with varying temperature regimes. The fire continued until the source of fuel was completely consumed, as the relevant services were unable to perform their duties in the temporarily occupied territory.

The temperature of the fire load in the apartments was determined by analysing the characteristic signs of damage in the materials from which the building structures, equipment, and residents' property were made. An investigation of structures with varying degrees of damage allowed us to determine the maximum temperature impact on the load-bearing and enclosure structures [1,22].

We assessed the temperature that occurred during the fire using specific examples of damaged materials, building structures, and equipment.

The charring of wood remains (complete charring to the entire depth) indicated fire exposure of up to 1300°C. An examination of the glass (window units) in the apartment on the 4th floor revealed melting and hardening in the form of drops, indicating a temperature effect of up to 850°C. Various materials made of aluminium and its alloys, brass, copper, bronze, and cast iron inside the apartments also showed significant melting with droplet formation, suggesting a temperature range of 600-1200°C (these limits are approximately determined by the melting temperatures of individual metals and their alloys).

The behaviour of concrete under heating is influenced by changes in the aggregate and cement matrix. The most characteristic signs that indicate the effect of fire temperature on reinforced concrete and masonry structures are associated with discolouration and soot deposition. Decreases in sound tonality during concrete tapping, peeling and chipping of concrete, explosive and localized destruction, changes in plastic and deformable characteristics, physical and chemical properties of concrete and reinforcement, fire erosion areas, and melting of reinforcement are typical for reinforced concrete structures during a fire.

In some apartments, the reinforced concrete lintels and parts of the round hollow floor slabs were covered with soot. Additionally, there was a lagging of the reinforcement from the concrete in the floor slabs, concrete spalling, and sagging of individual round hollow slabs in areas where the fire load was concentrated (Fig. 3). The concrete exhibited a reddish hue. Moreover, the prefabricated reinforced concrete round hollow floor slabs were delaminated along the ribs between the hollows and had sagged. Other observed damage included the falling of gypsum plasterboard finishes, peeling of plaster, changes in the brick surface colour, and soot deposits on the walls.

Fig. 3. The damage to the prefabricated reinforced concrete round hollow floor slabs

It is worth noting that the working reinforcement of prefabricated reinforced concrete round hollow floor slabs was heated to 300-800°C (assuming a concrete cover of at least 15 mm in diameter) under fire conditions lasting up to three hours. Such a temperature regime significantly impairs the physical and mechanical properties of the reinforcement and its adhesion to the concrete. A pale grey shade of the concrete and the absence of soot suggest a combustion temperature above 900°C, as soot burns off completely at this temperature.

Layer separation of masonry to a depth of more than 100 mm, along with the separation and flaking of the mortar surface, the formation of cracks, and slight chipping of the corners of individual bricks, were observed in the masonry of the middle and front walls of apartments in the fifth entrance across three floors. These damages indicate the effect of fire on a hollow sand-lime brick wall at temperatures above 800°C (Fig. 4). Additionally, we detected the plaster falling from brick walls, as well as the layer separation and discolouration of bricks.

3. Research results

A missile struck the third (five-storey) section approximately in its centre during air strikes on the city's infrastructure. The building suffered significant (emergency) damage due to the ensuing fire. Because fire-fighters were unable to perform their duties, the fire spread to part of the apartments at the fifth entrance of the eight-storey section (Figs 1, 2). The fire continued until the combustible materials in the building's apartments were completely burned out. Consequently, the fire load varied significantly depending on the individual property of the residents in each apartment.

The impact of the fire load on individual apartments was extremely severe. On the third floor, all the apartments were completely destroyed by the fire. In these apartments, the gypsum plasterboard partitions collapsed entirely (Fig. 4).

Fig. 4. The damage to the brick walls and gypsum plasterboard partitions

The prefabricated reinforced concrete round hollow floor slabs delaminated along the ribs between the hollows and sagged (Fig. 3). In the sand-lime brick masonry, there was complete flaking of plaster and discolouration of bricks to a depth of more than 100 mm and 120 mm (Fig. 4). As a result, the outer walls lost up to 120 mm of their cross-sectional thickness, and the inner walls along axes ‘B’ and ‘B/2’ were reduced to 240 mm in thickness (120 mm on each side, respectively).

Despite the gypsum plasterboard finishing falling off, it is notable that the wall surfaces covered with it withstood the fire load much better than those plastered according to individual residents' decisions. This situation further confirms the high fire resistance of gypsum plasterboard and its potential for increasing the fire resistance of structures. The fire load, as indicated above, caused the destruction of partitions, delamination and sagging of the prefabricated reinforced concrete round hollow floor slabs, plaster peeling, changes in brick surface colour, and soot accumulation on the walls (Fig. 3).

Due to their massiveness, the prefabricated reinforced concrete lintels were in much better condition than the prefabricated reinforced concrete round hollow floor slabs. The lintels experienced surface layer separation of concrete and a reduction in sound tonality when tapped, indicating concrete damage to a depth of 28 mm. However, unlike the prefabricated reinforced concrete floor slabs, their physical destruction did not occur.

In the fourth entrance, all apartments were unaffected by the fire. The damage to these apartments was solely due to the blast wave, resulting in the complete or partial destruction of windows and doors. Cracks on the surface or adjacent to load-bearing structures indicated defects in the gypsum plasterboard partitions.

The restaurant premises on the first floor of the second section were also completely burnt out.

The decision to preserve the second section of the residential building, which has two entrances, was made after assessing the emergency damage to the load-bearing structures. Given the destruction of 20% of the floor slabs and 16% of the load-bearing walls, a decision was made to restore the destroyed structures of the second section. This decision was economically justified and significantly reduced the time required to return residents to their homes as soon as possible.

To restore the prefabricated reinforced concrete round hollow floor slabs damaged by the fire, it was decided to replace them with a monolithic floor on metal beams using I-beam No. 22, spaced 1200 mm apart. A reinforcing mesh with working reinforcement of Ø 8 mm A400C and distribution reinforcement of Ø 6 mm A240 with a pitch of 200 mm was then laid on the lower flanges. The concrete used had a strength grade of C20/25, and the thickness of the monolithic reinforced concrete floor slabs was 90 mm. The slab was poured 15 mm below the lower edge of the I-beam to ensure fire resistance. Extruded polystyrene was laid on the slab to bring the floor level in line with the preserved existing prefabricated floor. Afterward, a finishing screed with a thickness of 40 mm was laid on top of the newly constructed floor structure. The floor structure was then placed on this finishing screed (Fig. 5).

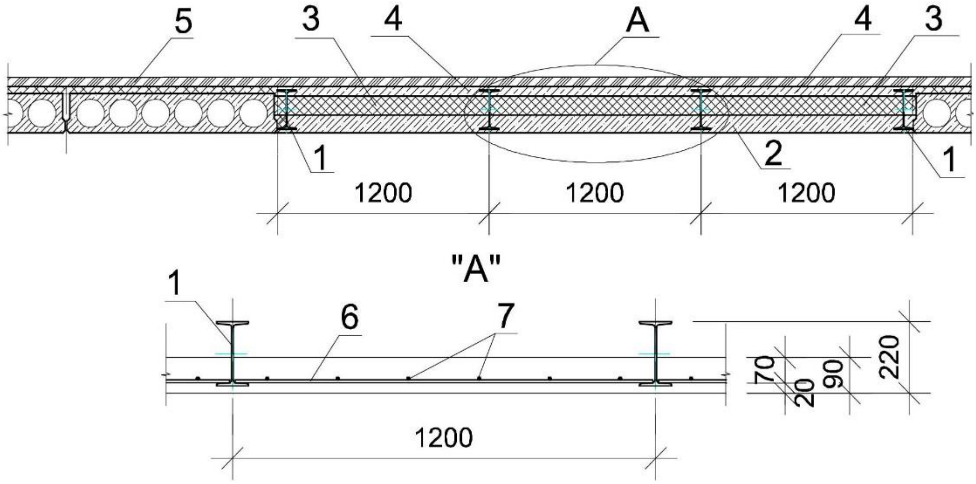

Fig. 5. Replacement of the floor from prefabricated reinforced concrete round hollow floor slabs to a monolithic floor on metal beams: 1 – I-beam No. 22; 2 – reinforced concrete monolithic slab (concrete grade C20/25, thickness 90 mm); 3 – extruded polystyrene foam; 4 – finishing screed (thickness 40 mm); 5 – floor design; 6 – reinforcement Ø 8 mm A400C (spacing 200 mm); 7 – reinforcement Ø 6 mm A240 (spacing 200 mm)

Damaged load-bearing walls made of sand-lime bricks were restored by installing a jacket made of reinforced shotcrete. Before installing this jacket, the walls were cleaned of plaster remnants, delaminated bricks, and soot. Then, reinforcing meshes with cell sizes of 250 x 250 mm were installed over the entire storey height. Vertical reinforcement rods with a diameter of Ø 10 mm and horizontal reinforcement rods with a diameter of Ø 8 mm were used, both made from A400C class reinforcement. These meshes were placed on both sides of the wall and connected with reinforcing clamps made of A240 class reinforcement, with a diameter of Ø 8 mm and spaced 500 x 500 mm apart. The clamps were installed in pre-drilled holes in the masonry. After this, shotcrete was applied, with a strength of M250 (C20/25). The thickness of the jacket was 40 mm, ensuring the complete filling of any lost masonry volume (Fig. 6).

Damaged gypsum plasterboard partitions with a thickness of 100 mm were replaced by partitions made of aerated concrete blocks. These blocks were reinforced with wire (diameter 4 mm) every three rows (900 mm). Slots with prefabricated reinforced concrete lintels, where the depth of concrete destruction due to fire load reached the reinforcement, were strengthened by installing lintels made of steel equal-sided or unequal-sided angles, depending on the load acting on them. The walls must be insulated with rigid mineral wool slabs and then protected with decorative facade finishing to bring the external walls of the building up to regulatory energy efficiency requirements.

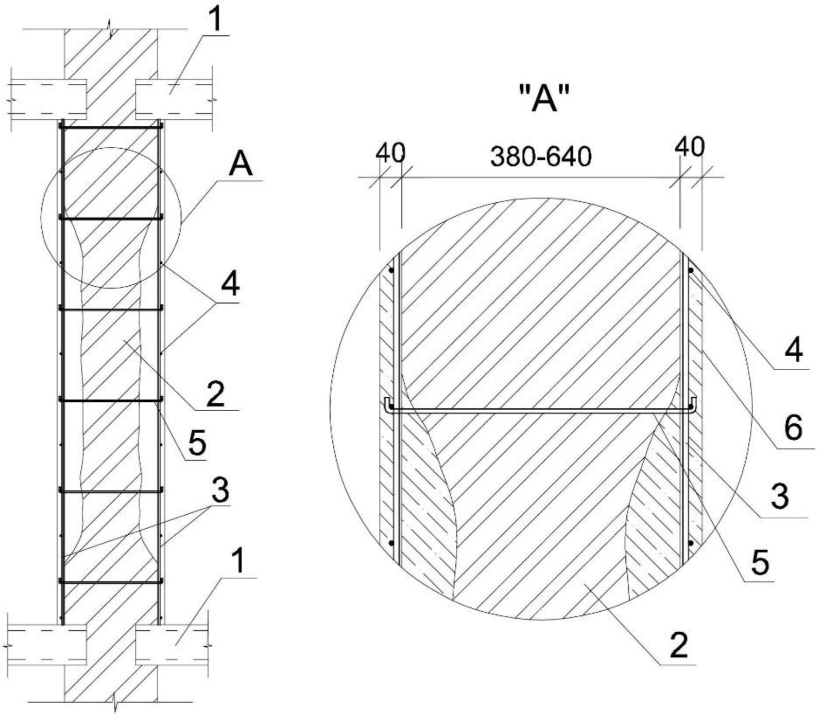

Fig. 6. Restoration of the masonry by installing a shotcrete jacket: 1 – floor; 2 – brick masonry; 3 – vertical rods of reinforcing mesh (diameter 10 mm, spacing 250 mm, reinforcement class A400C); 4 – horizontal rods of reinforcing mesh (diameter 8 mm, spacing 250 mm, reinforcement class A400C); 5 – reinforcement clamps (diameter 8 mm, spacing 500 x 500 mm, reinforcement class A240); 6 – shotcrete (strength M250 (C20/25))

4. Conclusions

Due to the war in Ukraine, a significant number of buildings and structures have sustained varying degrees of damage or have been completely destroyed. The visual and instrumental studies, combined with the determination of temperature effects on specific examples of damaged building materials, enabled a step-by-step approach to removing the load-bearing structures of an apartment building from an emergency condition with maximum accuracy.

A detailed analysis of defects and damage to the load-bearing structures of the multi-apartment residential building after exposure to an uncontrolled fire load allowed for the restoration of the eight-storey second section. The fire load resulted in the complete collapse of gypsum plasterboard partitions, delamination and sagging of prefabricated reinforced concrete hollow floor slabs along the ribs between the hollows, plaster falling away from sand-lime brick walls, detachment of brick walls to a depth of 120 mm, and discolouration of the brick walls.

Due to the destruction of 20% of the floor slabs and 16% of the load-bearing walls, it was decided to restore the damaged structures in the second section of the building at the fifth entrance. The emergency prefabricated reinforced concrete round hollow floor slabs should be completely replaced with a monolithic floor on metal I-beams. Load-bearing walls made of sand-lime bricks, damaged by fire, should be restored by installing jackets made of reinforced shotcrete. Damaged gypsum plasterboard partitions should be replaced with aerated concrete blocks, which will be reinforced during construction. Prefabricated reinforced concrete lintels, where the depth of concrete destruction has reached the reinforcement, should be strengthened with steel angles. The external walls of the building have been adapted to regulatory energy efficiency requirements by insulating them with rigid mineral wool slabs.

The proposed design solutions for strengthening the floors and walls, based on the results of the survey, are scientifically grounded in engineering principles and provide the required load-bearing capacity of these structures. These decisions will prevent further deterioration of the residential building and help residents return to their homes as soon as possible.

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