

PANELS OF COLD-FORMED STEEL PROFILES: POSSIBILITY OF THEIR USE TO REPAIR WAR-DAMAGED LARGE-PANEL BUILDINGS

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Abstract

In the paper, we present the results of an analysis of data samples of 282 damaged buildings; the samples include the age of the building, the type of vertical bearing structures, the type of construction of the external walls, the method of the insulation of the walls, the number of floors, the buildings' functions, and the extent of the damage. The primary objective of the analysis was to evaluate the possibility of using panels of cold-formed thin-walled steel profiles to repair the damaged structures. The results of a study of typical projects of large panel buildings that were constructed in Ukraine and an analysis of the practical experience of repairing these types of buildings after blast actions can also be found. The research tasks are defined for implementing this technology in the process of repairing large panel buildings.

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Key words

- Large-panel buildings,
- Reinforced concrete panels,
- Cold-formed steel structures,
- Lightweight panels,
- Repairs after a war,
- War damage.

1 INTRODUCTION

As of 1 June 2022 (Lotočka, 2022), approximately 116,000 buildings, including 12,300 multi-storey buildings, have been damaged due to the active phase of the war in Ukraine, which started on 24 February 2022. Despite ongoing combat actions in Ukraine, programs for repairing damaged buildings are already on the way. For example, the RepairHouse " programme " (Vidnovidim) from the Energy Efficiency Fund was created for homeowners' associations to fund repair work on damaged buildings due to the invasion of the Russian Federation in Ukraine. For repairing and renovating damaged buildings, it is expedient to apply technical decisions that allow them to be completed quickly.

At the same time, in Ukraine, DSTU 9194:2022 has been in effect since 1 June 2023. This standard regulates the use of pa-

nels made from cold-formed, thin-walled steel profiles (CFSP or PCFSP panels). The application of these panels could be one method to quickly and reliably repair damaged large-panel buildings and frame buildings with already existing hinged reinforced concrete panels. The replacement of damaged reinforced concrete wall panels for PCFSP will permit the production and installation of this type of panel in the fastest amount of time without the need for heavy lifting equipment in dense urban conditions. Using this type of panel does not increase the weight of a wall's structures (versus filling the opening with bricks or lightweight concrete blocks), thereby creating a frame that braces the existing reinforced concrete panels. Additionally, this technical solution is energy efficient and will increase living comfort after the renovation. The primary goal is to estimate the possibility of repairing war-damaged large-panel buildings using panels of cold-formed thin-walled steel profiles

2 MATERIALS AND METHODS

The external walls are the largest envelope structures by area in multi-storey buildings. Therefore, the probability that these walls are damaged after shelling is greater than for other parts of a building. This makes research on the types of wall construction damage very realistic. The exterior walls differ in the type of material, mounting method, and method of load transfer from other structures. Repairability is an important parameter for any structure under the conditions of military operations. Repairability is the ability of a structure to have its serviceability restored after failure, i.e., reparability influences the level of failure and/or size of the damage. In our research, we will distinguish three groups of damage: local damage, destruction of part of a building, and damage in which any repair is not feasible.

The expediency of using PCFSP to repair damaged buildings can be determined from an analysis of the existing damage to buildings in Ukraine. For this analysis, we used a data sample from 282 photos of damaged buildings. These photos come from open sources, news websites, and news channels. The names of the sources and the sites of the photos will not be presented in the article (except for a few with characteristic damage on Fig. 1) to prevent the use of this information for non-scientific purposes. The data sample does not include buildings with fully destroyed structures and buildings with insignificant damage to envelope structures (such as broken windows and doors, damage to the insulation layer, tracks of small fires

etc.). In the analysis, the buildings have had significant mechanical damage to the walls. Not included in the data sample were industrial buildings, but some buildings with double functions, warehouses, and shops, were mentioned. All the photos were taken and published in open sources before 1 September 2022.

Each photo was analysed to determine the following parameters of a building:

1. Year of construction (before 1945, 1945-1965, 1965-1980, 1980-1995, 1995-2010, after 2010).
2. Type of vertical bearing structures: full frame, incomplete frame (with load-bearing external walls and internal columns), frameless (with longitudinal and/or transverse bearing walls).
3. Type of external walls: reinforced concrete panels (large panels), bricks, lightweight concrete blocks, steel panels, glass panels, and large concrete blocks.
4. Method of wall insulation: without an insulation layer, External Thermal Insulation Composite Systems (ETICS), ventilated facades.
5. Number of floors
6. Function of the building: dwelling, public, or commercial (warehouse, store, mall).
7. The volume of damages: local (the opening in a wall from a missile; destruction or absence of a panel or concrete block; absence of part of the wall); destruction of

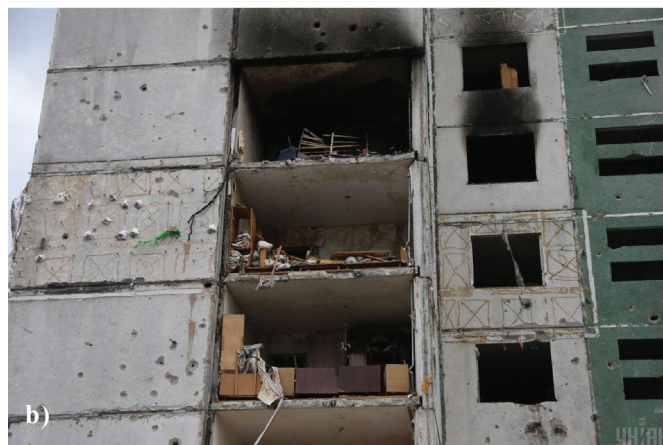
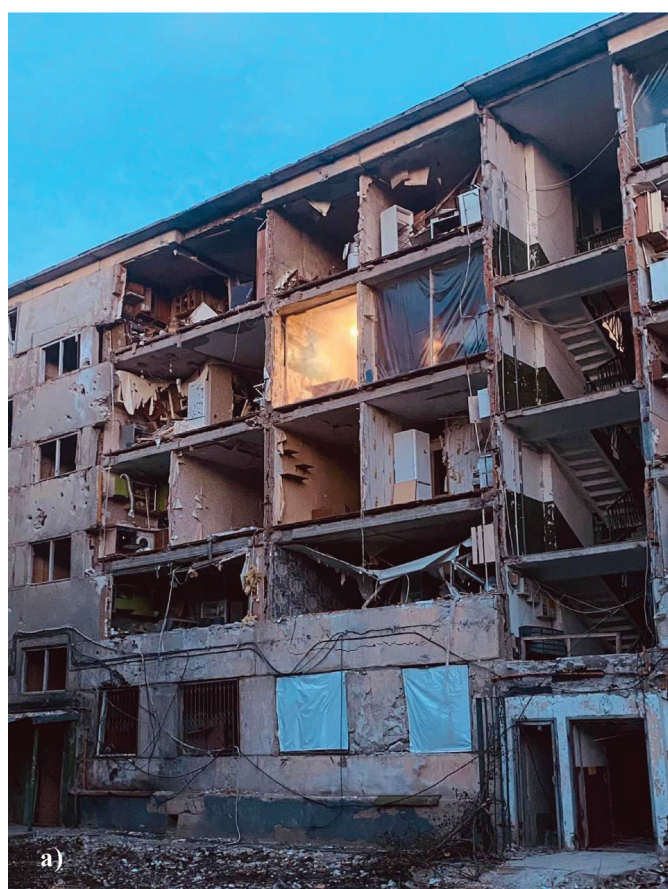


Fig. 1 Examples of partially destroyed large-panel buildings

(sources: a) Information at <http://tiny.cc/y4e4vz>; b) Information at <http://tiny.cc/05e4vz>; c) Information at <http://surl.li/evqbf>)

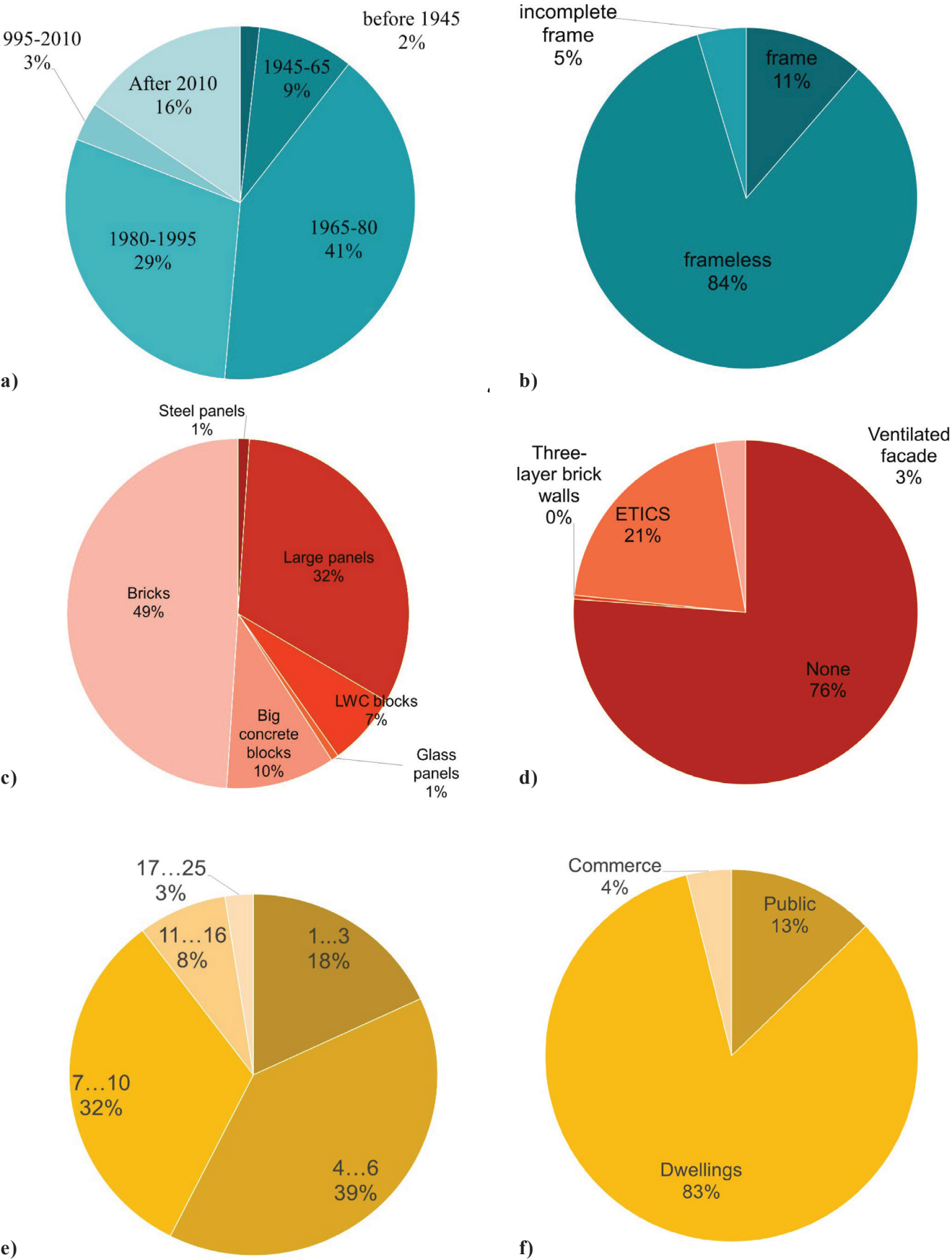


Fig. 2 Diagram of the percentage distribution of damaged buildings by: a) year of construction; b) type of vertical bearing structures; c) type of external walls; d) method of wall insulation; e) number of floors; f) function of the building

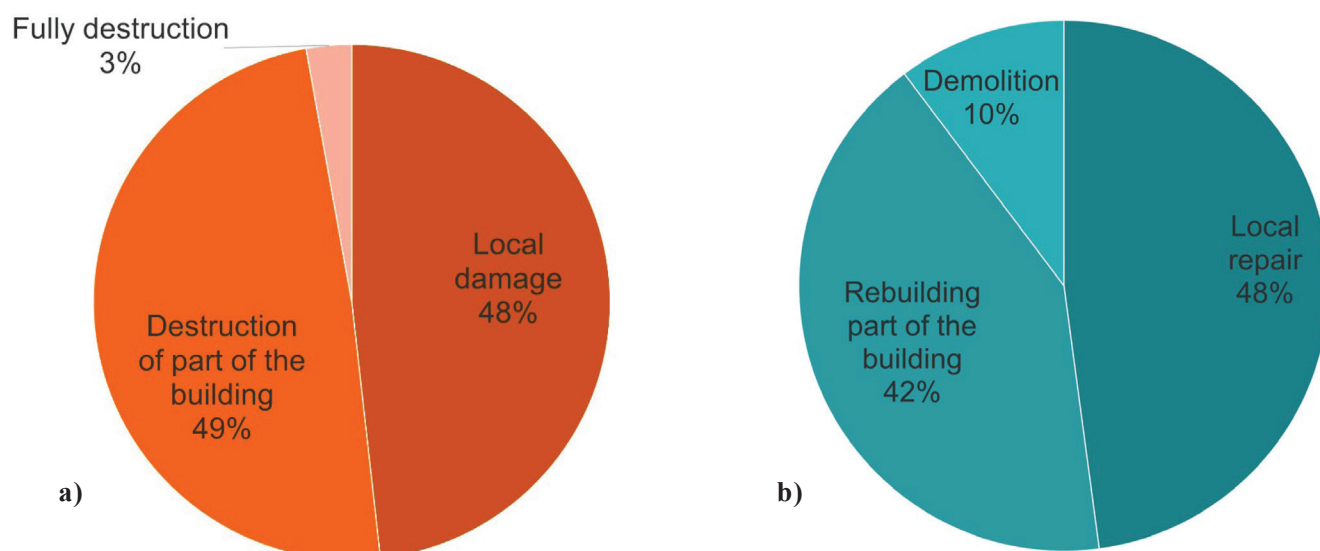


Fig. 3 Diagram of the percentual distribution of the damaged buildings by: a) extent of damage; b) method and possibility of repair.

part of the building (partial destruction of two or more types of bearing structures, for example, destruction of part of the wall and part of a floor) and damage in which repair is impractical (this category for the buildings which, after careful analysis, were recognised as dangerous).

8. Method and possibility of repair: local repair, rebuilding a part of the building, and demolition.
9. Conclusion about the possibility of using PCFSP to repair damaged buildings.
10. Solutions for using PCFSP: as a separate panel or as a system of panels.

The results obtained are based on the experience of the authors of the article.

3.1 Research on types of damage to wall constructions of civilian buildings during the war in Ukraine

The distribution of damaged buildings by the year of construction is shown in Fig. 2a. The year of construction was defined by periods. The entry of the building into the period was identified by the architectural planning decisions of the building pictured. The two most massive groups of damaged buildings (a total of 70%) are buildings constructed in 1965-1980 (41%) and 1980-1995 (29%). These are the buildings of the first massive series of construction and their later and improved variants. The third place was for a group of modern buildings that were constructed after 2010 (16%).

The diagram in Fig. 2b shows that most of the damaged buildings are frameless, with bearing walls as the vertical bearing elements. The second largest group is the frame buildings, i.e., 10% of the total amount of damaged buildings. Most of the frame buildings were constructed after 2010.

The largest part of the damaged buildings had walls made from bricks, i.e., 49% of the total quantity (Fig. 2c). The second group had walls made from reinforced concrete panels (32%). The third group (10%) had walls of large concrete blocks. In

summary, these three groups covered buildings of all the construction periods. Walls of lightweight concrete blocks (7%), steel panels (1%), and glass panels (1%) were commonly related to buildings constructed after 2010 with a frame structure.

Seventy six percent (76%) of the damaged buildings did not have additional wall insulation (Fig. 2d). However, that is 9% less than the number of buildings constructed before 2010 (before the active implementation of the requirements of the first edition of DBN V.2.6, so we can conclude that from the data sample selected, nearly 10% of the buildings constructed before 2010 were modernised by thermal insulation. Twenty one percent (21%) of the buildings had external thermal insulation composite systems (ETICS), and 3% had ventilated facade systems. One building had three-layer brick walls with a mineral wool insulation middle layer.

Fig. 2e includes a distribution diagram of the damaged buildings by the number of floors. Buildings with 4-6 storeys (39%) and 7-10 storeys (32%) had more damage. Low-rise multi-apartment buildings and public buildings comprised 18% of the damaged buildings. The high-rise buildings amounted to 11%, which is quite a large group. The most significant group of damaged buildings (43%) has more than six storeys and indicates a need to develop lightweight wall systems for the repair of walls of that height.

Residential buildings are the largest group of damaged buildings, i.e., 83% (Fig. 2f); public buildings (schools, play schools) amounted to 13%; and large malls and other commercial buildings amounted to only 4 % of the total.

Despite the prefiltering of the photos of fully destroyed buildings, 3% of the damaged buildings were classified as fully destroyed after a careful analysis of the photos (Fig. 3a). Almost half of the buildings had local damage (48%), and 49% of the buildings had a destroyed part. Based on these data, it is possible to conclude (Fig. 3b) that 48% of damaged buildings can be repaired and that 10% of the damaged buildings have undergone extensive damage and must be demolished without any additional investigation. This means that not all of the buildings with destroyed parts can be rebuilt.

Out of the total quantity of damaged buildings that can be repaired (Fig. 4), it is possible to repair a total of 33 build-

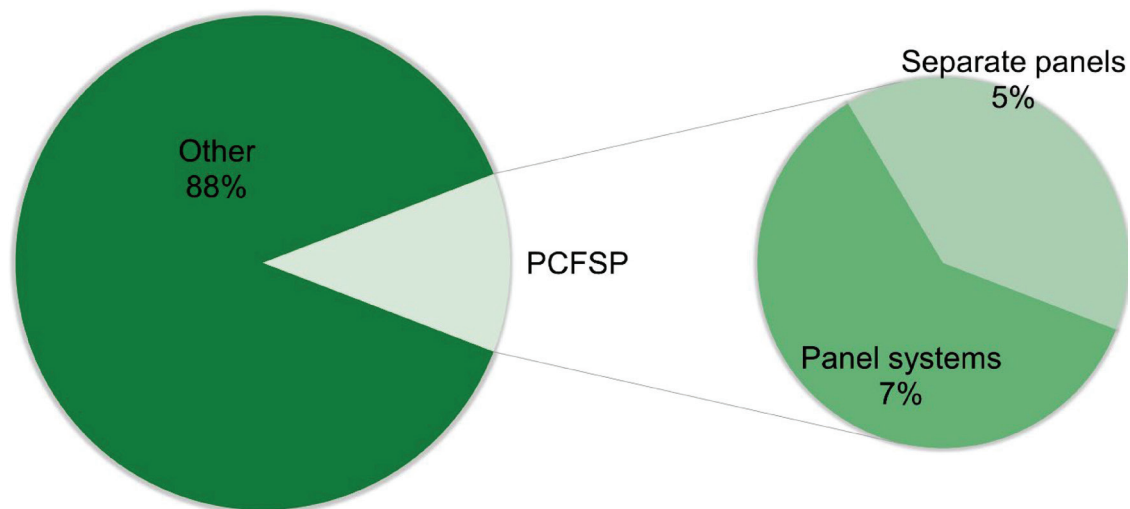


Fig. 4 Percentual distribution diagram of buildings that could be repaired using panels from cold-formed steel profiles (separate panels or panel systems)

ings with separate CFSP panels (5%) and CFSP panel system (7%). Of these buildings, 15 buildings were constructed in 1965-1980; 9 buildings were constructed after 2010; and 8 buildings were constructed in 1980-1995. Twenty one (21) buildings have large panel walls; eight buildings have walls made from lightweight concrete blocks; four buildings have steel panels, brick walls and big concrete blocks. Fifteen buildings are frameless; 14 buildings have a frame, and 4 have an incomplete frame.

From the analysis provided, we can conclude there is a possibility of using wall panels from cold-formed thin-walled steel profiles to repair damaged or missing reinforced concrete panels in large-panel buildings, frame buildings with hinged reinforced concrete panels (buildings of schools, public buildings, etc.), and frame buildings with walls made of lightweight concrete blocks.

The general requirements for the manufacture and installation of wall panels from cold-formed thin-walled steel profiles are presented in DSTU 9194:2022 and European Technical Assessment ETA 13/0312. They can be directly used for the renovation and repair of frame buildings. The possibility of using this technology to repair damaged buildings made from large-panel elements requires an additional analysis of the technical documentation for this type of building and an analysis of the experience of the repair of large-panel buildings after blast actions. These analyses are presented below.

3.2 Review of structural solutions for large panel buildings constructed in Ukraine

The issue of using PCFSP in the renovation of existing large-panel buildings was not present before the start of the active phase of the war in Ukraine. Designing PCFSP to repair large panel buildings requires the provision of an analysis of structural solutions for this type of building constructed in Ukraine. We need information on the thickness of the external panels, the methods of mounting panels to the supporting structures, and the function of the panels in the behaviour of all the bearing and enclosure structures.

The construction of the buildings from reinforced concrete panels occurred through typical projects and series that were developed at the end of the 1950s and modernised step-by-step in the following years. According to information from researchers on Kyiv (Agieieva et al., 2021), more than 5000 large panel buildings were constructed in the 1960s to 1970s in Ukraine, the majority of them from series 1-464 (20.85%) and 1-480 (18.3%). The same data are presented in Denisenko (2012) and the Report on research work under Contract No. 16-417/2021. As of 2011, Denisenko (2012) reported that large panel buildings constituted 47% of the total number of multi-storey buildings in Ukraine. Series 1-464 was created by the “Giprostroyindustiya” Experimental Institute. The buildings were four and five storeys tall; the building construction scheme had longitudinal and transverse bearing walls. The walls were of two types, i.e., external: three-layer (two external layers of reinforced concrete and a middle insulation layer) or a single layer of lightweight concrete; internal, i.e., single-layer made of reinforced concrete with a thickness of 120 mm. The distance between the transverse walls was 2.6 and 3.2 m. According to (Pleshkanovska and Biriuk, 2020), the buildings of series 1-464 were five and nine storeys tall. The thickness of the external walls in Kyiv is 350 mm. Series 1-480 was developed by the KyivZDIEP Institute with parameters very close to those of series 1-464.

(Filonenko et al., 2018) noticed that in the 1980s, the building series 111 was actively implemented; it had external concrete panels of keramzit (expanded clay aggregate) with thicknesses of 300 and 350 mm and internal panels with thicknesses of 120 and 160 mm. The external panels consisted of a keramzit concrete core layer with thicknesses of 260 and 310 mm and two external layers of sand-cement mortar with a thickness of 20 mm each.

The analysis of the existing project documentation on multi-storey dwellings from the 1960-1995 construction years was provided by researchers from NDIBK and HNUMG (Album of technical solutions, 2012; Report on research work under Contract No. 16-417/2021). They divided all the enclosed structures of existing buildings by their materials and thicknesses as follows:

- lightweight concrete, lightweight concrete-facing ceramic tiles – external walls with thicknesses of 300, 350 and 400 mm (series 1-480, 1-467, 96, K-134, BPS-6, APPS, T, 87);
- three-layer panels with effective insulation material – external walls with thicknesses of 300 and 350 mm (series 1-464, 1-463, KT-12-16, 96);
- double layer – external walls with a thickness of 350 mm (series 1-335);
- aerated concrete – exterior walls with thicknesses of 250 and 300 mm (series 1-468, 1-464Ya);
- ceramic brick or silicate brick – exterior walls with thicknesses of 380 and 510 mm (series 1-438, 1-447, KP, 67, 87);
- lightweight brick masonry – exterior walls with a thickness of 380 mm (series KP, 67, 87).

Based on the above, the thickness of the external panels for large panel buildings varied from 300, 350 and 400 mm, depending on the material, region, and year of construction for a particular building. As a rule, single-layer keramzit concrete panels in Ukraine were used with thicknesses of 300-350 mm. The thicknesses of the internal walls were 120 and 160 mm. The walls were made of B20 concrete (modern analogue: C15/20).

The vertical and horizontal structures of large panel buildings work together through special vertical and horizontal joints. It should be noted that the joints of structures for different series (Series 1-464A, 1967; Series 125, 1970, 1978; Series 2.130-1, 1975 a, b; Typical project 1-464A-3, 1963) do not practically differ. The depth of the support of the floor panels, according to (Series 1-464A, 1967; Series 125, 1970, 1978; Series 2.130-1, 1975 a, b; Typical project 1-464A-3, 1963; Maklakova et al., 1986; Shereshevsky, 1981), on the exterior walls is 90 mm. Panel joints in large panel buildings must have a complex solution considering the requirements of strength, corrosion protection, thermal insulation, permeability to air and moisture, sound insulation, and the possibility of performing work in any season (SN 321-65).

As a rule, the internal wall panels and floor panels in large panel buildings are joined on a horizontal plane as platform joints (the joint when the load from above the lying panel is conducted to the bottom panel via the floor panel). The resistance to the tensile forces in vertical joints is achieved by steel connection elements welded to the steel bars of the panels. The contact of the concrete surfaces transfers the compressive forces in horizontal joints through a layer of mortar or other materials, which ensure the strength and density of the joint.

According to SN 321-65, the connection of transverse and longitudinal wall panels is based on the following principle: if the edge side of the transverse panels enters the joint between the longitudinal wall panels, a connection occurs at two points. If the transverse panel does not reach the joint between the longitudinal wall panels, then the connection must be made with concreted steel bars, at no less than three levels, but at a distance no greater than $10h$ (where h is the thickness of the wall).

The calculations related to large panel buildings are complicated and multifactorial. If the bearing capacity of the transverse walls is sufficient for their resistance to vertical forces, the external panels can be analysed only for the load from their self-weight (Dykhovichny, 1970).

To conclude our analysis of structural solutions for the large panel buildings that were constructed in Ukraine, we can state:

- The thickness of the external walls is 300-350 mm. The walls are mainly a single layer of keramzit concrete. The dimensions are: width – 2.6 m, 3.2 m (in one room) and 5.9 m or 6.0 m (in two rooms). The height of the panels is 2.7 m;
- The thicknesses of the internal walls from C15/20 concrete are 120 mm and 160 mm;
- External walls according to static function are bearing and(or) self-bearing;
- The external walls resist horizontal forces, which act on the plane of the walls, via a special construction of vertical joints, and can involve a cross-section of the wall when calculating the rigidity of the whole building;
- The external walls are located between two internal walls. They resist the load from the floor plate and from the weight of the panels standing above and transfer part of these loads to vertical panels through vertical monolithic key joints.

Based on the complexity of the structural calculations of large panel buildings and the random character of the probable damage as a result of combat actions, it is recommended that each building be considered as a unique structure and that a decision about the correct retrofit method for a building be based on certain defects and damages that occurred during its erection and exploitation, and during the war conflict.

Based on the analysis of literary sources, series and typical projects, we can say that there are no direct objections to the use of lightweight frame panels as external panels in the regulatory documentation and requirements for large panel buildings.

3.3 Analysis of experience in the repair of damaged large panel buildings

Large panel buildings were mainly built in European countries. Most publications on the thermal insulation modernisation of this type of building, for example, have already been cited (Report on research work under Contract No. 16-417/2021; Filonenko et al., 2018; Album of technical solutions, 2012). A comprehensive analysis of papers on the exploitation of large panel buildings of the 21st century was done by (Malazdrewicz et al., 2022). In 1990, a “Recommendation for the repair and strengthening of prefabricated buildings by polymer solution” was developed; it presents recommendations for the repair and strengthening of large panel buildings. However, there is no recommendation about repairing mechanical damage and openings. (Malganov et al., 1990) developed “Atlas schemes and drawings” for the repair and strengthening of building structures. In the Atlas they presented a few examples of strengthening large panel buildings, but none of them cover replacing one or some of the panels in an existing building. (Mackiewicz et al., 2022; Ligęza, 2014; Szulc and Piekarczyk, 2022) dedicate themselves to liquidating operational damage and defects in large panel buildings and provide valuable information on the problem of repairing large panel buildings after explosive action.

(Malakhova and Balakshin, 2014) analysed the damage to a nine-storey building with large external panel walls. As a result of a gas explosion on the eighth floor, the bearing structures of the upper-lying floors were destroyed. As a result of an investigation, it was decided to repair part of the building with monolithic reinforced concrete structures. The same situation, but for a ten-storey building, was described in (Kumpyak et al., 2013). As a result of the explosion of a gas cylinder, the floor and wall panels on the last two floors of a building were destroyed. The building was renovated. First, a part of the attic and the tenth and ninth floors were demolished; then the building was fully rebuilt using new large panels.

(Hryhorovskiy et al., 2022) covers the approach of using BIM to monitor the technical condition of damaged buildings during a war and make decisions about renovation. The approach was approved during the monitoring of the technical situation of a large panel building in Kyiv, which was partially destroyed by a domestic gas explosion. Special attention was paid to strengthening it with load-bearing functions. The damage to the building was critical, so that part of the building was demolished.

The positive experience of the renovation of a large panel building in Kharkiv that was damaged in 2012 by a domestic gas explosion is described in (Reznik et al., 2022). The renovation project included partially replacing the existing large concrete floor plates with new monolithic concrete (on floors 9-11) and to strengthening the existing floor plates and internal bearing wall panels, (Shmukler et al., 2013) described repairing the external wall structures in more detail. For the repair, the enclosed structures used steel frames with rigid joints filled with foam-concrete blocks. The outer part of this structure was insulated with mineral wool with a thin plaster layer. Furthermore, (Reznik et al., 2022) have emphasised the problem of

creating a new solution for the repair of large panel buildings because they believe the lack of large panel production capacity will not permit this type of building to be restored according to large panel technology.

You can see photographs of the repair process of buildings, including large panel buildings (Fig. 5). The (Fig. 1a) photo shows the renovation process of a building using the installation of new lightweight self-supporting lightweight concrete walls instead of large panels. The advantages of this method are not evident. This method is not industrial, and it is impossible to repair all of the damaged infrastructure, which includes thousands of multi-apartment buildings. This is why the possibility of developing industrial (or prefabricated) solutions, which enable maximum work to be done on the ground and the erection of panels on any floor using simple lifting mechanisms, is unquestionably realistic.

4 CONCLUSIONS

An analysis of war-damaged buildings in Ukraine shows that damage to wall structures can be repaired using panels from thin-walled cold-formed steel profiles. For 12% of the damaged buildings in the data sample, it is possible to use this technology. For the renovation of frame buildings with panels, the CFSP can use the recommendation of DSTU 9194:2022. The largest group of damaged buildings are large panel buildings (32%). An analysis of typical projects, series, and scientific and normative publications on this issue finds no limitation in the use of lightweight steel frame panels in the technology of large panels. The experience of renovating large panel buildings after gas explosions shows the possibility of recovering buildings by different methods, including using steel



Fig. 5 The repair process of a large-panel building (sources: Information at <https://cdn4.suspilne.media/images/resize/1040x1.78/680874f014cfdd08.jpg>)

frames. The plan for future work includes the development of principal schemes for CFSP panels to repair large panel buildings. The structural solution of the panels must be approved by calculating the requirements of mechanical strength, stability, and energy savings.

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