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APPLYING MODERN CONSTRUCTION 4.0 TECHNOLOGY TO DAMAGED BUILDINGS

Abstract. *The work purpose was to conduct a comparative analysis investigating the damage caused to a high-rise building (HRB) under dynamic impacts of two types: periodic industrial explosions at the iron ore quarry of «UGOK» mining and processing plant in Kryvyi Rih and a rocket strike on HRB in Kyiv on February 26, 2022. fib bulletin 59 was used as the basis. The study demonstrates how the life cycle curve of HRB transforms under periodic dynamic impacts and a one-time combat action influence compared to the standard fib bulletin 59 curve. The applied methods included visual and instrumental inspection of buildings using non-destructive testing methods, geodetic and vibration instruments with IoT for refining initial-boundary conditions during the creation of the HRB Construction 4.0 (Digital Twins). Therefore, its experimental verification was conducted. The calculation package LIRA-CAD was used for calculations. It can be noticed while comparing vibration displacement projections at identical points of buildings 6-A and 6-B. Under current conditions, the operational lifespan of 6-A decreases by approximately $\Delta T \approx 30$ years. To restore the building to a safe technical state, allow residents to return, and extend its operational lifespan beyond the current estimate (≈ 70 years), comprehensive restoration work is required. A methodology for using a Construction 4.0 (Digital Twins) as an element of the straightening control system has been developed. It allows for the adjustment of tilt-eliminating works based on the current monitoring and calculation of the digital spatial model of the multi-story building and the stress-strain state of the "reshaped soil base – tilted strip foundation" system. The successful implementation of the methodology is also demonstrated. A multi-story building in Zaporizhzhia, Ukraine, was straightened without relocating the residents or shutting down essential utilities (elevators, water supply, etc.). Three stages of Digital Twin (Construction 4.0) formation for the specified objects are considered: formation of a Digital Model; formation of Digital Twins, when methods and means of non-destructive testing are involved, and the last stage – Digital Twin, when the results and recommendations of the results of the first two stages are taken into account when reconstructing or restoring the original physical object for the Digital Twin.*

Keywords: *Construction 4.0, Digital Twin, high-rise building, stress-deformed state, forecasting, Internet of Things.*

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Introduction

The aging of building structures over time is an unavoidable phenomenon faced by humanity throughout history. The general evolution of a building's life cycle – from commissioning to demolition – is depicted in Figure 1 from fib Bulletin 59 [1]. However, deviations in the rate of progression along this curve frequently occur, either accelerating or decelerating. Examples of decelerated degradation include ancient monuments, such as the Pantheon [2] and the Colosseum in Rome, which have not only survived but continue to serve as heavily utilized sites, welcoming numerous visitors daily.

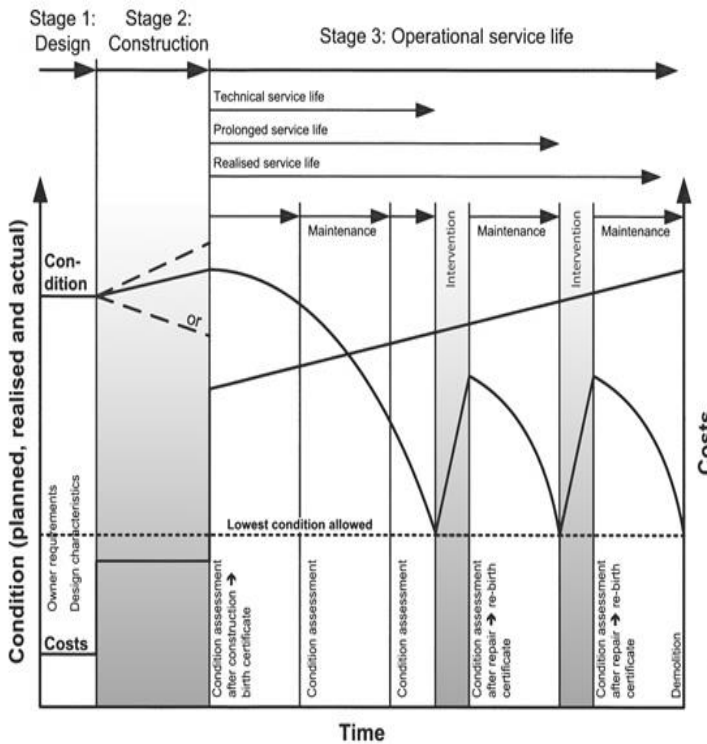


Fig. 1. The entire service life of a building from "birth" to "death"

The latter scenarios often fall within the domain of forensic engineering. Many scientists, engineers, and builders worldwide have addressed these challenges to varying extents. Notable contributions are documented in works [3], which were considered in this study for a comparative analysis of the life cycle degradation of buildings due to periodic industrial explosions at the “PivdGZK” quarry in Kryvyi Rih and a rocket strike on a high-rise building in Kyiv on February 26, 2022.

Impact of Industrial Explosions at the Open-Pit Iron Ore Quarry of the Southern Mining and Processing Plant on Surrounding Buildings

The open-pit iron ore quarry of “PivdGZK” in Kryvyi Rih was established in 1952 and has reached a depth of approximately 250 m. At the surface level, mining operations are conducted within an area delineated by an oval with major and minor

axes measuring 4 km and 3 km, respectively. The explosion safety zone is defined as 700 m. The boundary of the residential areas in the Inhulets District of Kryvyi Rih, located east and southeast of the quarry, lies 800–900 m from the eastern edge of the pit. Consequently, when blasting occurs on the upper levels of the quarry, the explosion safety zone comes extremely close to the residential areas. The dynamic impacts on buildings within the explosion safety zone are periodic. Until recently, blasting operations at “PivdGZK” were conducted every two weeks, with the maximum amount of explosives used per blast ranging from 490 to 652 tons during the observation period from 2008 to 2012. Buildings selected for monitoring during the blasting activities included: The Church of the Nativity of the Virgin Mary (hereafter referred to as the “Church”) located at 14 Obrucheva Street (Figures 2), Middle School No. 40 on Sestroritska Street (Figure 3), The Youth Creativity Center (hereafter referred to as the “Center”). These structures are sites of mass gatherings and must meet heightened safety requirements, making their comprehensive analysis critically important [4-7].



Fig. 2. Church's reaction to the explosion in the quarry. Top – cracks in the brick vault of the Church. Bottom – the priest pointing out vertical cracks on his house located within the Church's premises



Fig. 3. Visual inspection of School No. 40 revealed cracks up to 0.05 m wide in external load-bearing walls. Crack gauges and vibration monitoring are required to assess seismic and explosion-related impacts

The Center in Kryvyi Rih was selected for detailed experimental and theoretical investigations, as well as for assessing its residual lifespan, partly due to the availability of design documentation. The building was designed in 1960 and constructed during the 1970s, a period of intensive iron ore extraction at the quarry. Consequently, the

structure was subjected to seismic impacts from explosions during its construction phase (Figure 7) [4, 5]. The comprehensive methodology for determining the residual lifespan of buildings in zones affected by dynamic impacts includes the following steps: 1) visual inspection of the building to document damage; 2) determination of the physical and mechanical properties of the building's structural elements and dynamic measurements to assess its response and identify natural frequencies (required for verification of the analytical model); 3) development of a graphical model of the building incorporating findings from Step 1 (Figure 5) [5, 6]; 4) identification of the analytical model; 5) dynamic stress-strain state calculations for the building; 6) assessment of the structural risk; 7) construction of the building's life cycle curve and quantitative evaluation of its residual lifespan. The detailed description of Steps 1–7 can be found in the dissertation by V. Dunin under the scientific supervision of Prof. Iu. Kaliukh [4]. The results of the Center's resource depletion due to regular industrial explosions are shown in Figure 4 [4].

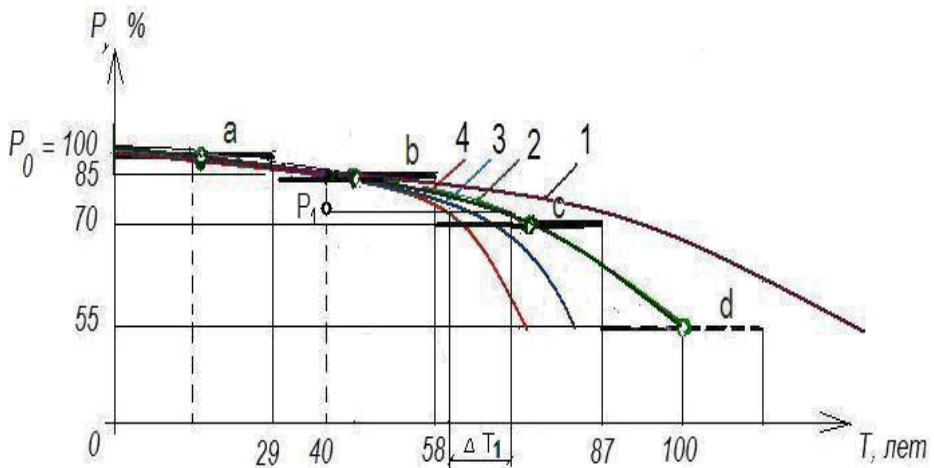


Fig. 4. Curves of bearing capacity changes: 1 – for a specific structural element under dynamic impacts; 2 – for the building as a whole without seismic impacts; 3 – for the building as a whole under dynamic impacts without damage; 4 – for the building as a whole under dynamic impacts with damage; a – building in normal condition; b – building in satisfactory condition; c – building unfit for normal operation; d – building in an emergency condition; P1 – technical condition of the Center building at the time of investigation

The reduction in the building's lifespan is determined by the loss of load-bearing capacity. The calculated age of the building differs from the actual age by approximately 30 years. Observed defects during visual inspections, combined with analytical and experimental data, indicate that the overall technical condition of the Center can be classified as unfit for normal use in the fore-seeable future. As internal defects in the building accumulate, the risk of failure in its reinforced concrete load-bearing structures will increase, accelerating aging and further reducing its lifespan.

Impact of a Missile Strike on a High-Rise Building and the Reduction of Its Residual Lifespan

During the war, Russia has destroyed or damaged over 210,000 buildings in Ukraine, according to an analysis conducted by The New York Times in collaboration with remote sensing experts Corey Sher from the Graduate Center of the City University of New York and Jamon Van Den Hoek from Oregon State University (Figure 5) [8].

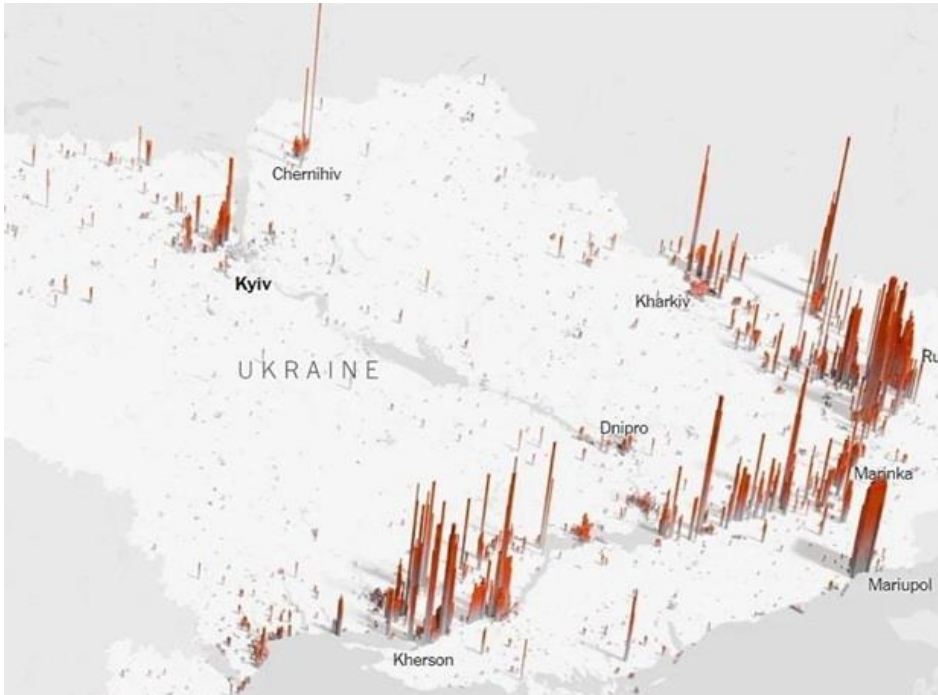


Fig. 5. Visualization on the map of Ukraine of the analysis results for destroyed or damaged buildings conducted by The New York Times in collaboration with remote sensing experts Corey Scher from the Graduate Center of the City University of New York and Jamey Van Den Hoek from Oregon State University [8]

Their study used radar satellite data capable of detecting even minor structural changes. Approximately 900 of the damaged or destroyed buildings are protected under the Geneva Conventions, including 106 hospitals, 109 churches, and 708 schools. Many cities and villages are literally wiped off the face of the Earth or at least severely damaged, and an actual destruction may be far more large-scale. In May 2024, Ukraine's Prime Minister Denys Shmyhal stated that Russia had destroyed or damaged 250,000 only residential buildings, about 4,000 schools, more than 1,000 hospitals, and numerous other civilian buildings. The total damage from the invasion was estimated at \$486 billion [9].

The investigation was conducted on the high-rise building at 6-A Lobanovskyi Avenue in Kyiv, which suffered significant damage from a missile strike on February 26, 2022 (Figure 6, Figure 7).

The study evaluated the technical condition of the building and its suitability for further use. The following activities were performed: a general inspection of the building and a detailed inspection of the damaged section (axes 1–5/G–K) to identify

structural damage; engineering and geodetic measurements of vertical and horizontal displacements of the building; instrumental testing of the actual concrete strength of the building's pylons; calculation of a spatial model of the building under static and dynamic loads; determining forces in the remaining elements considering the destruction of some load-bearing components; verification of the actual state of the pylons and their elements; calculation of the actual stress-strain state of the building (Table 1 from the dissertation by S. Kurash, conducted under the scientific supervision of Prof. Iu. Kaliukh [6]). The findings were compiled into a technical report on the building's condition.

These pylons must either be reinforced or replaced. Therefore, additional urgent anti-collapse measures were recommended, along with technical solutions for strengthening and partially re-placing damaged building structures. The reduction in the building's lifespan is depicted in Figure 8. Before the missile strike (Point A, identical to Point B), the building at 6-A had no damage, and its structural performance curve matched the load-bearing capacity curve of a similar building at 6-B Lobanovskyi Avenue (Figure 8).



Fig. 6. General view of the building at 6A Lobanovsky Avenue after the rocket impact on April 26, 2022

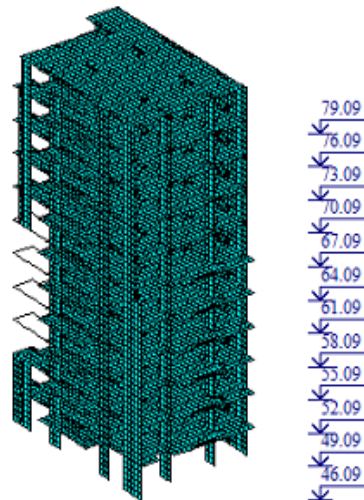


Fig. 7. Digital Shadow of the building at 6A Lobanovsky Avenue in Kyiv with damaged elements on floors 18-21

After sustaining damage, the dynamic characteristics of the building 6-A at Lobanovskyi Avenue, Kyiv, changed (frequencies, amplitudes, etc.), as shown at Point A'. The building becomes unsuitable for normal use (Zone c), demonstrates increased susceptibility to displacements. It can be noticed while comparing vibration displacement projections at identical points of buildings 6-A and 6-B. Under current conditions, the operational lifespan of 6-A decreases by approximately $\Delta T \approx 30$ years. To restore the building to a safe technical state, allow residents to return, and extend its operational lifespan beyond the current estimate (≈ 70 years), comprehensive restoration work is required.

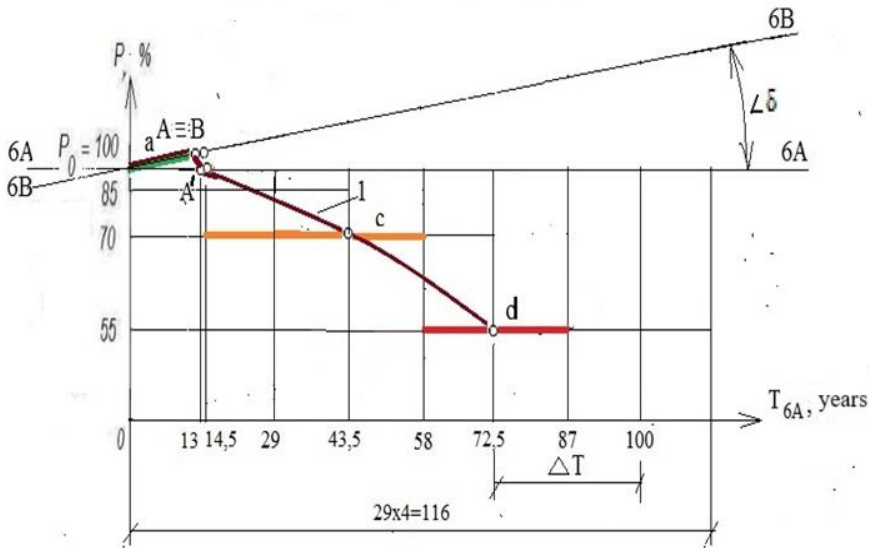


Fig. 8. The bearing capacity change as functions of time for building 6-A at Lobanovskyi Avenue, Kyiv

Eliminating the excessive tilt of a 9-story large-panel building using Digital Twins

The structural scheme of the building is frameless, with plan dimensions of 24x12 meters. The spatial rigidity is ensured by load-bearing longitudinal and transverse walls made of expanded clay concrete with a thickness of 0.35...0.45 meters, as well as reinforced concrete floors. During operation, the building was subjected to subsidence deformations. The longitudinal and transverse tilts reached excessive values. As a result of calculating the Model of the building for the impacts and loads that occurred during operation, its 3D SSS was obtained from the combined effect of external loads and subsidence deformations, along with node displacements of the Model for each of the calculation options [10, 11]. The principal stresses in the building elements were calculated and analyzed, providing an assessment of the strength of the materials in its structural elements. Since the building did not meet the conditions for normal operation due to excessive tilts caused by subsidence deformations, it was decided to eliminate these tilts. The building's tilt was corrected by drilling the calculated amount of soil from under the foundation's footing. For this, a trench was dug along the building facade to a depth of one meter below the foundation. The weakening of the base layer (compacted loess loam) was achieved by drilling two rows of horizontal cylindrical boreholes up to 15 meters long with variable diameters of 0.16...0.22 m. Moistening the borehole walls accelerated the process of technological settlements to the required value. The work to form the building's counter-tilt lasted 14 days. Uneven settlements of the building in the longitudinal direction were achieved at 0.041...0.055 m, and in the transverse direction – at 0.092...0.178 m (see Fig. 9).

To determine the building's SSS based on residual deformations and compare them with the values obtained from monitoring data, the Model calculations were continuously performed, simulating the straightening process. The deformation impacts were numerically modeled in stages according to feedback from

experimental observations of the building's behavior. During the tilt correction process, the deformation and force characteristics gradually stabilized, and the stresses in the system reached safe values. Fig. 6 and Fig. 7 shows the changes in node displacements and the distribution of principal stresses in the building's structures during the straightening process. The conducted studies on the changes in the building's SSS allow us to conclude that during the straightening of the building by local reshaping of the soil base through drilling horizontal cylindrical boreholes, the stresses that arise in the load-bearing structural elements do not always decrease and, in some cases, may exceed the allowable values for the construction materials. This can be explained by: (1) the complex response of the spatial structural system of a multi-story building to external impacts; (2) the uneven distribution of stiffness in its elements; (3) the presence of defects; and (4) zones of critical stress. The developed methodology for adjusting the Model based on feedback from experimental MIMS data in real-time allows for control of the building's SSS parameters.



Fig. 9. General view of the deformation seam between block sections No. 3 and No. 1 before straightening (a); and after straightening (b) at 23, 25, Engineer Preobrazhenskyi St., Zaporizhzhya, Ukraine [10]

Conclusion

1. A comparative analysis was conducted to investigate the damage to buildings under two types of dynamic impacts: periodic industrial explosions at the "PivdGZK" iron ore quarry in Kryvyi Rih and a one-time missile strike on a high-rise building in Kyiv on April 26, 2022, based on fib Bulletin 59. The study has demonstrated how the life cycle curve of buildings is transformed under periodic dynamic impacts and one-time impacts from hostilities compared to the standard building lifecycle curve [4, 5].

2. The information-measurement system "Monitoring," which allows for real-time tracking of the stress-strain state parameters of the multi-story building, has been incorporated into the straightening control system. It enables the adjustment of tilt-elimination works based on current monitoring and calculations of the digital spatial model of the multi-story building and the stress-strain state of the "reshaped soil base – tilted strip foundation" system. Therefore, a methodology for using Digital Twin as an element of the system controlling the tilt elimination process has been developed.

3. The methodology was implemented during the straightening of an actual multi-story building in the city of Zaporizhzhia, Ukraine. Mechanical drilling of horizontal cylindrical boreholes was selected as the most rational method for reshaping the base soil and eliminating the building's tilt. The weakening of the base soil was achieved by drilling two rows of horizontal cylindrical boreholes up to 15 meters long with variable diameters of 0.16...0.22 m. Moistening the borehole walls accelerated the process of technological settlements to the required value. The work to form the building's counter-tilt lasted 14 days. Uneven settlements of the building in the longitudinal direction were achieved at 0.041...0.055 m, and in the transverse direction – at 0.092...0.178 m [10, 11].

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ЗАСТОСУВАННЯ СУЧАСНОЇ ТЕХНОЛОГІЇ CONSTRUCTION 4.0 ДЛЯ
ПОНІВЧЕНИХ БУДІВЕЛЬ

Анотація. Метою роботи було проведення порівняльного аналізу пошкоджень, завданих висотній будівлі (ВБ) динамічними впливами двох типів: періодичними промисловими вибухами на залізорудному кар'єрі гірничо-збагачувального комбінату «УГЗК» у Кривому Розі та ракетним ударом по ВБ у Києві 26 лютого 2022 року. За основу було використано бюлетень fib 59. Дослідження демонструє, як трансформується крива життєвого циклу ВБ під впливом періодичних динамічних впливів та одноразового впливу бойових дій порівняно зі стандартною кривою бюлетеня fib 59. Застосовані методи включали візуальний та інструментальний огляд будівель з використанням методів неруйнівного контролю, геодезичних та вібраційних приладів з Інтернетом речей для уточнення початково-граничних умов під час створення ВБ Construction 4.0 (Цифрових двійників). Тому було проведено його експериментальну перевірку. Для розрахунків було використано розрахунковий пакет LIRA-CAD.

Розроблено методологію використання Construction 4.0 (Цифрових двійників) як елемента системи керування випрямленням. Це дозволяє коригувати роботи з усунення нахилів на основі поточного моніторингу та розрахунку цифрової просторової моделі багатоповерхової будівлі та напружено-деформованого стану системи "переформована ґрунтова основа – похилий стрічковий фундамент". Також продемонстровано успішне впровадження методології. Багатоповерхову будівлю в Запоріжжі (Україна) було випрямлено без переселення мешканців або відключення важливих комунікацій (ліфти, водопостачання тощо). Розглянуто три етапи формування Цифрового двійника (Будівництво 4.0) для зазначених об'єктів: формування Цифрової Моделі; формування Цифрових двійників, коли задіяні методи та засоби неруйнівного контролю, та останній етап – Цифровий двійник, коли результати та рекомендації результатів перших двох етапів враховуються під час реконструкції або відновлення оригінального фізичного об'єкта для Цифрового двійника.

Ключові слова: Будівництво 4.0, Цифровий двійник, висотна будівля, напружено-деформований стан, прогнозування, Інтернет речей.

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