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Original Empirical Research

Correlations of Damage to the Main Structures of Industrial Buildings from their Service Life

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Abstract

Introduction. Well-known studies on the research subject have failed to specify sample sizes and types of workshops based on their technological characteristics, which prevents us from summarizing the numerous damage data. The downside of the previous studies is the lack of generalizations with designing regression dependences of damage to the bearing elements of buildings on their service life. The subject of the study is the correlation of damage to the main structures of industrial buildings from their service life. In order to design these dependencies, a significant sample of workshops (at least 100 workshops) has been investigated and the frequency of damage to their main structures has been examined. The frequency of damage has been previously studied and published by the authors. The aim of the study is to establish correlations between the degree of damage and the service life of structures.

Materials and Methods. The objects of the study were single-storey industrial buildings of the metallurgical, machine-building, energy industries, as well as production of building materials. The workshops were inspected by means of the standard methods endorsed in the national standards and norms. In order to analyze defects and damages, an electronic database was designed in a tabular processor that recorded all the basic information on types of workshops, materials and structures, defects and damages.

Research Results. The analysis of data on a large sample of industrial buildings made it possible to establish correlations between damage and the service life of structures. It was found that the rate of damage to steel columns is higher than that of reinforced concrete columns. The intensity of damage to steel columns is described by means of an exponential dependence, while that of reinforced concrete columns is a linear one. Brick and reinforced concrete walls are damaged linearly depending on the service life. The dependence "damage - service life" of reinforced concrete floors and coatings is approximated by a polynomial of the second degree, close to a linear relationship. Similar linear damage is typical of steel trusses. The damage rate of steel crane beams does not directly depend on the service life of the building itself, as the beams are replaced if damaged.

Discussion and Conclusion. As a result of the study of the frequency of damage, mathematical models of "damage - service life" of industrial building structures were obtained that can be used in order to optimize maintenance and repairs of buildings. The distinctive features of the accumulation of damages and defects over time for metal frames of industrial buildings associated with human mistakes are noted. In order to reduce accidents and optimize costs throughout the life cycle of buildings, it is suggested that a risk-based approach is applied, the likelihood of errors and cost of restoration measures at the stages of design, construction and operation are assessed.

Keywords: industrial buildings, building maintenance, construction accidents, defects and damages, reliability and safety

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Оригинальное эмпирическое исследование

Корреляции поврежденности основных конструкций промышленных зданий от сроков их эксплуатации

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Аннотация

Введение. В известных исследованиях по теме статьи не указываются объемы выборки и типы цехов по их технологическим признакам, что не позволяет обобщить многочисленные данные о повреждениях. Недостатком ранее проведенных исследований является отсутствие обобщений с построением регрессионных зависимостей повреждаемости несущих элементов зданий от сроков их эксплуатации. Предметом исследования являются корреляции поврежденности основных конструкций промышленных зданий от сроков их эксплуатации. Для построения указанных зависимостей исследована значимая выборка цехов (не менее 100 цехов), и изучена частотность повреждений их основных конструкций. Частотность повреждений была изучена ранее и опубликована авторами. Целью настоящего исследования является построение корреляций между степенью поврежденности и сроками эксплуатации конструкций.

Материалы и методы. В качестве объектов исследования рассматривались одноэтажные промышленные здания металлургической, машиностроительной, энергетической отраслей, а также производства строительных материалов. Обследование цехов производилось по стандартным методикам, утвержденным в национальных стандартах и нормах. Для анализа дефектов и повреждений была создана электронная база в табличном процессоре, в которой фиксировалась вся основная информация по типам цехов, материалам и конструкциям, дефектам и повреждениям.

Результаты исследования. Анализ данных по большой выборке промышленных зданий позволил установить корреляции между поврежденностью и сроками эксплуатации конструкций. Установлено, что скорость повреждений стальных колонн больше, чем у железобетонных. Интенсивность повреждений стальных колонн описывается экспоненциальной зависимостью, а железобетонных — линейной. Кирпичные и железобетонные стены повреждаются по линейной зависимости от сроков эксплуатации. Зависимость «повреждаемость — сроки эксплуатации» железобетонных перекрытий и покрытий аппроксимируется полиномом второй степени, близким к линейной зависимости. Подобная линейная повреждаемость характерна и для стальных ферм. Повреждаемость стальных подкрановых балок прямо не зависит от сроков эксплуатации самого здания, так как балки заменяют по мере их повреждений.

Обсуждение и заключение. В результате исследования частотности повреждений были получены математические модели «поврежденность — срок эксплуатации» конструкций промышленных зданий, которые могут быть использованы для оптимизации технического обслуживания, планирования экспертиз, периодических осмотров, текущих и капитальных ремонтов зданий, разработки стратегии предприятий по замене основных производственных фондов. Отмечены отличительные особенности накопления со временем повреждений и дефектов для металлических каркасов промышленных зданий, связанные с человеческими ошибками. Для снижения аварийности и оптимизации затрат на протяжении жизненного зданий предлагается применять риск-ориентированный подход, оценивать вероятность возникновения ошибок и стоимость восстановительных меприятий на стадиях проектирования, возведения и эксплуатации.

Ключевые слова: промышленные здания, эксплуатация зданий, строительные аварии, дефекты и повреждения, надежность и безопасность.

Для цитирования. Байбурин Д.А., Потапов А.Н. Корреляции поврежденности основных конструкций промышленных зданий от сроков их эксплуатации. *Современные тенденции в строительстве, градостроительстве и планировке территорий*. 2026;5(2):56–65. https://doi.org/10.23947/2949-1835-2026-5-2-56-65

Introduction. According to the estimates of the Russian Academy of Architecture and Building Sciences (RAABS) [1] there is a need to develop a regulatory framework based on ensuring the integrated safety of objects throughout their full life cycle. This calls for scientific research to be conducted, including studies of durability of building materials, structures and products as well as of longevity of construction sites.

According to [2–4], the causes of defects and damage to industrial buildings are deficiencies in construction — 28%; violation of operating rules — 26%; poor quality of materials — 28%; design mistakes — 10%; deficiencies in design standards as well as guidelines for manufacture and installation of structures — 8%. The observed frequency of defects in installation of steel and reinforced concrete structures [5] confirms these conclusions. The number of defects in joints and assemblies for steel structures is 56.5%, and for reinforced concrete structures — 57.7%.

According to [2, 3], the proportions of accidents related to the operational stage has gone up from 11% to 35%, which is due to the deterioration of the country's fixed assets (industrial buildings and infrastructure). This trend is particularly evident for industrial buildings that are characterized by large spans and severe operating conditions associated with aggressive environments, lifting equipment, dynamic loads, etc.

Accidents involving coatings on industrial buildings should be considered the most common ones. An analysis of accidents shows that about 53% of all collapses occur as a result of overloading with snow and dust [6]. According to [7, 8], the following damage to rafter trusses occurs for the main buildings of thermal power plants: local rod bends — 28%; wear of anticorrosive coating and metal corrosion — 23%; general bends of rods of trusses — 24%; accumulations of aggressive technological dust on structures — 9%; non-nodal plate support on the upper belt of trusses — 6%.

A damage rate of structures depends on service life [7, 8] (comparison for 20 and 80 years of service life): reinforced concrete and steel columns — an increase from 10 to 20%; reinforced concrete and steel crane beams — from 10 to 70%; steel rafter trusses — from 15 to 40%; coating plates — from 20 to 60%; secondary reinforced concrete platform beams — from 15 to 80%; main reinforced concrete platform beams — from 10 to 25%.

A regular decrease in the number of damages from top to bottom, ranging from coating plates and trusses to columns, as well as rapid fatigue wear of crane beams, was identified. According to [9], the number of damaged crane beams increases from 14 to 73% with an increase in the service life from 3 to 22 years. The most common damage to beams is fatigue cracks in the belt seams of the upper belt.

Studies [10, 11] describe typical defects in steel columns: bends and cutouts of lattice elements, local bends and curvature of tent and crane branches, destruction of attachment points of crane beams as well as changes in a typical structural design of joints. The most frequent damages are used in computer modeling in order to assess a degree of serviceability of metal structures of industrial buildings [12].

The authors of [13] identified five characteristic areas of defects and damage to walls of buildings. It is suggested that they are combined into groups when conducting surveys or monitoring the condition of a facade. This allows one to track the dynamics of negative processes and conduct major repairs of facades in a timely manner. In [14], the damage was analyzed with an indication of their causes. The frequency of damages and defects is determined by the types of structures, severity of defects, as well as their causes.

A study [15] suggests ways to enhance the reliability of industrial building frames: boosting the strength reserve by increasing cross-sections, the strength of materials, and the use of more efficient cross-sections; using statically indeterminate systems with a redistribution of forces at the time of local destruction; incorporating coupling (non-force) elements.

The review showed that damage to industrial buildings has been investigated time and time again, but these studies typically fail to specify sample sizes and types of workshops based on their technological characteristics, making it impossible to summarize the numerous data. The drawback of the previous studies is the lack of generalizations with the construction of regression dependences of damage of load-bearing elements of buildings on their service life, which does not allow to justify and plan a rational program of their operational control.

Materials and Methods. The objects of the research were 100 workshops — single-storey industrial buildings of the metallurgical, machine-building, energy industries, as well as production of building materials. The years of commissioning of the workshops ranged from 1902 to 2016: 1902–1940 — 10 objects; 1941–1970 — 61 objects; 1971–1990 — 21 objects; 1991–2016 — 9 objects.

According to the design scheme, the buildings were divided into frame, wall and frame-wall ones. According to the design and materials: full reinforced concrete frame; full metal frame; mixed frame (reinforced concrete and steel); stone load-bearing walls with various coating options.

Almost all of the buildings had lifting equipment in the form of overhead cranes and truss cranes with a lifting capacity from 2 to 280 tons with various operating modes: from repair to heavy (from 1K to 8K). The degree of aggressiveness of the environment was mostly classified as non-aggressive or mildly aggressive.

The following structures were considered as groups of the same type: foundations, columns, walls, crane beams and trusses, sub-trusses and rafter trusses, lanterns, slabs and coatings, connections along columns and coatings. In material design these structures were divided into stone (brick, cinder block, butte), reinforced concrete monolithic and prefabricated, steel, wooden. In most cases, the roof of the surveyed buildings was rolled, less frequently metal.

The workshops were inspected according to the standard methods endorsed in the national standards and regulations. According to the guideline of the GOST 31937-2024 "Buildings and Structures. Rules for Inspection and Monitoring of Technical Condition" and SP 13-102-2003 "Rules for Inspection of Load-Bearing Building Structures of Buildings and Constructions", the work included identifying the geometric parameters of structures and assemblies, their compliance with the design and regulatory documentation; examination of the identified defects and damage, identification of their causes; instrumental control of the strength characteristics of the materials; specification of loads on load-bearing structures; verification calculations of damaged (defective) load-bearing and enclosing structures; identification of their technical condition; development of recommendations for repairing and strengthening building structures.

In order to analyze defects and damage, an electronic database was designed where the following information was recorded: the name of an object; structural type of a building; year of commissioning and of inspection; a brief description of a building structure; characteristics of lifting equipment; aggressiveness of the workshop environment; type of a structure, element and material of a construction; design and actual strength of a material; type and magnitude damage (defect); frequency of damage in the form of a ratio of damaged elements to the total number of elements in a building; localization and brief description of damage; cause of damage (defect); severity of defects in categories A, B and C; coefficient of reduction in the strength of a damaged element; category of technical condition of a structure; main recommendation for restoration.

Research Results. According to the data in Fig. 1, in terms of the degree of preservation characterized by the frequency of damage and categories of technical condition, steel and reinforced concrete structures are superior to stone ones.

This is directly due to the uniformity of the material, which has an impact on its resistance and durability, as well as the fact that stone walls are more susceptible to atmospheric erosion. On top of that, rapid damage to the corrosion protection of metal with low cross-section massiveness accounts for a frequent transition to a limited working condition of steel structures (45.3%). Roof and wooden roof structures ("other" in Fig. 1) very frequently transition into a limited working and inoperable state (92.5% of damage) due to a relative fragility of the materials and intense wear.

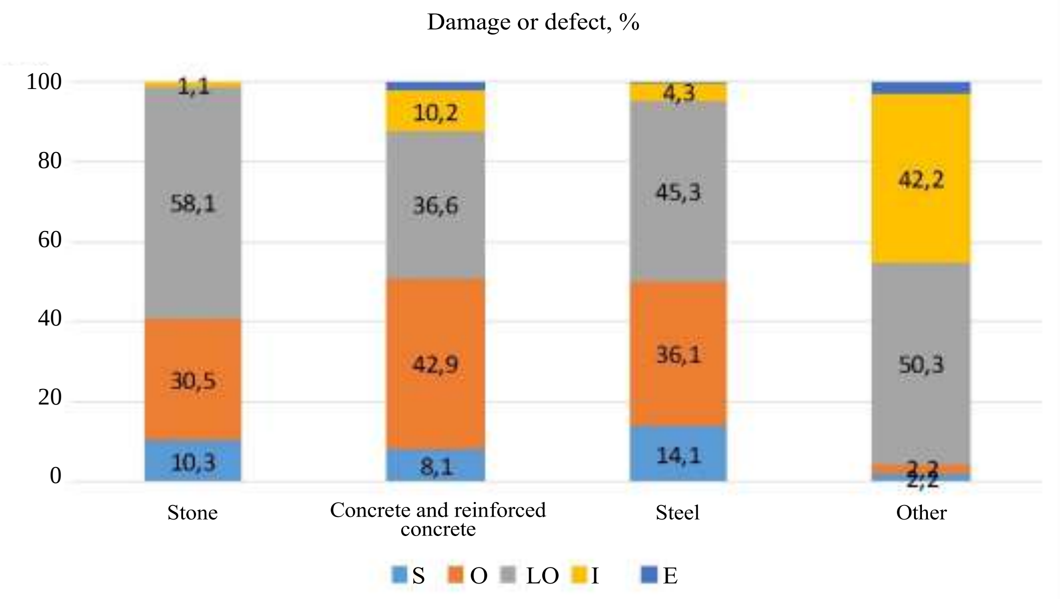

Fig. 1. Comparison of the categories of technical condition of types of constructions in %:
S — serviceable; O — operational; LO — limited operational; I — inoperable; E — emergency

Thus, the greatest degree of damage is observed in the structures forming a building shell: roof and covering, exterior walls, as well as structures located close to it. Studies have shown that the frequency of structural damage drops in the "top-down" direction: roof, covering, trusses, columns, etc.

The main causes of damage are roof and gutter leaks, wear phenomena (corrosion, humidification and defrosting, destruction of protective coatings, etc.), as well as effects of various production technologies (crane cyclic loads, accidental impacts by loads and workshop vehicles, cutouts of elements, aggressive environment, dust and scale accumulations, etc.).

The following are the results of investigating the dependence of damage on operating time. As the graphs (Fig. 2) suggest, reinforced concrete columns are damaged less intensively than steel ones. After 60 years of service life, about 20% of reinforced concrete columns and 30% of steel columns get damaged. After 100 years of service life, almost all steel columns will have been damaged.

A more intense damage to steel columns is primarily due to metal corrosion (over 40% of damaged columns). The intensity of damage to steel columns is described by an exponential dependence (Fig. 2). The accuracy of the approximation is satisfactory: the coefficient of determination R^2 = 0.788, the correlation coefficient is statistically significant.

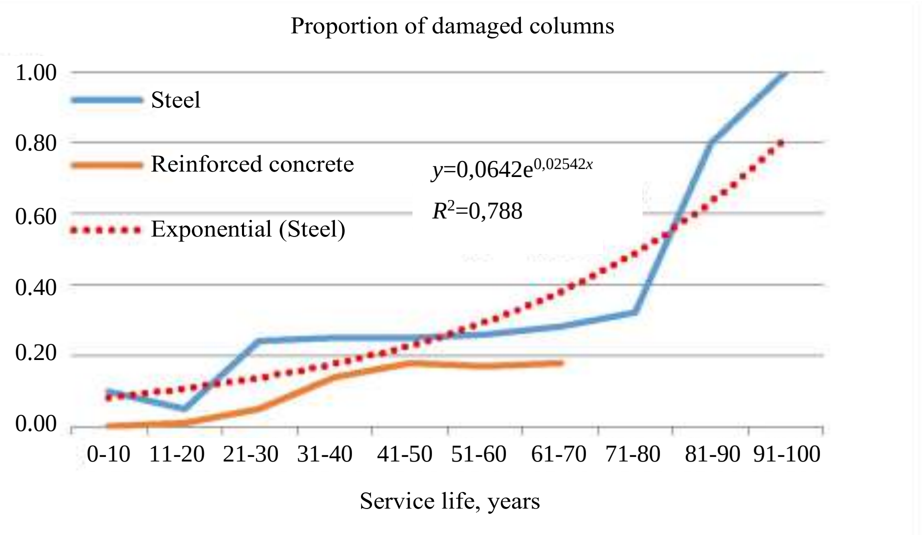

Fig. 2. Dependence of the column damage on service life

The coefficient of determination is calculated as the ratio of the sum of the squares of the regression residuals to the total sum of the squares:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(y_i - \hat{y}_i\right)^2}{\sum_{i=1}^{n}\left(y_i - \bar{y}_i\right)^2}.$$

At $R^2 \geq 0{,}95$ the accuracy of the approximation is high, at 0,8–0,95 — satisfactory, at 0,6–0,8 — weak, at $R^2 < 0{,}6$ — insufficient.

The average approximation error is the average relative deviation of the calculated values from the actual values y_i:

$$\bar{\varepsilon} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{y_i - \hat{y}_i}{y_i}\right|100.$$

If the error is no more than 10-15%, the model is deemed sufficient.

Brick and reinforced concrete panel walls are damaged linearly depending on the service life and with an approximately equal intensity of 0.7% per year (Fig. 3). After 60 years of service life, about half of the walls get damaged. The intensity of damage to brick walls is described by a linear relationship. The accuracy of the approximation is high (R^2 = 0,967).

The damage-time relationship of reinforced concrete floors and coatings is approximated by a second-degree polynomial close to a linear relationship of 1% per year (Fig. 4). The coefficient of determination R_2 = 0,95 is indicative of a high degree of accuracy of the model.

More than half of the damage to the slabs is due to soaking due to roof leaks and wear of internal communications. After 50 years of service life, about 40% of the plates get damaged, and after 50 years of service life, almost all the plates get damaged.

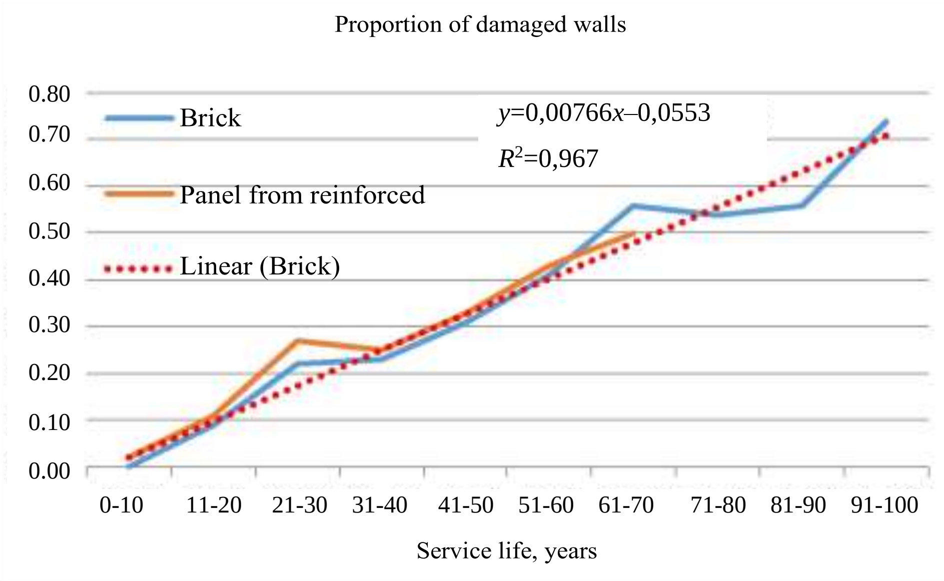

Fig. 3. Dependence of the wall damage on service life

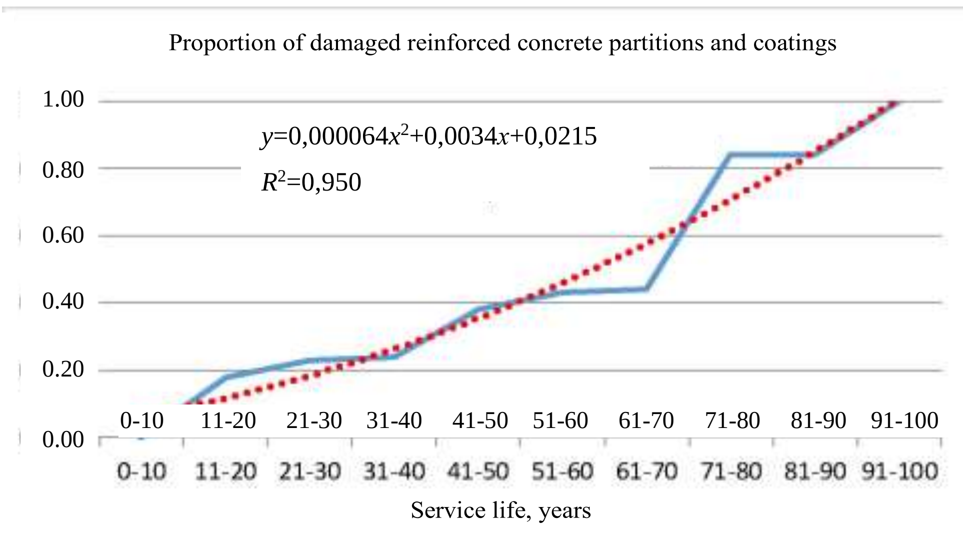

Fig. 4. Dependence of the floor damage on service life

The actual dependence of the proportion of damaged steel trusses (given the truss connections, rather than corrosion) is best modeled by a linear relationship (Fig. 5). The value of the coefficient of determination R_2 = 0.939 is indicative of a high accuracy of approximation.

As can be seen, unless corrosion is considered, about half of the steel trusses are damaged after 55 years of service life. Given the corrosion damage, 70% of steel trusses will have been damaged after 50–60 years of service life, and almost all trusses after 100 years of service life. Half of the damage to steel trusses is due to corrosion caused by roof and gutter leaks. Local bends of the elements have a frequency of 9.8%, the total bending of the rods is 5.9%.

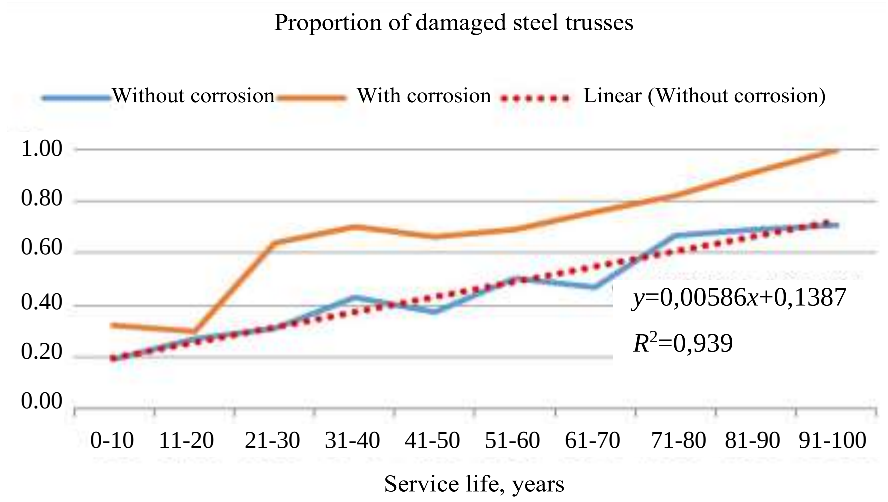

Fig. 5. Dependence of the steel truss damage on service life

From the obtained dependences of damage to the main load-bearing structures (Fig. 2–5), it can be concluded that the maximum service life of industrial buildings is 70-80 years long. By this time, the wear of load-bearing structures reaches 60–70%. During this time, the production technology has progressed significantly, which most frequently requires significant revamping of the production facilities.

The damage rate of steel crane beams does not directly depend on the service life of a building itself, as crane beams are the most damaged structures and are subject to periodic replacement. The most frequent damage to beams is metal corrosion (25.7%), broken fasteners (19.6%) and local damage to shelves and stiffeners (4.3%).

After averaging the damage data over 10 years (Fig. 6), it was found that the beams were changed with a frequency of about 20 years.

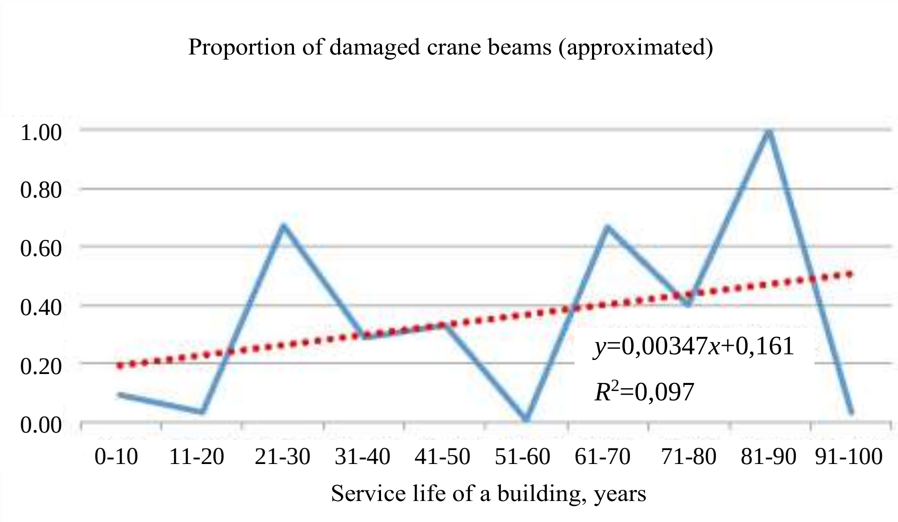

Fig. 6. Dependence of the average damage of crane beams on service life of a building (given a replacement)

According to the broken graph, the minimum damage values correspond to 20, 40, 60, 80 years of service life of a building. The time trend shows that as service life increases, so does the intensity of damage to crane beams, which might be due to a decrease in the overall rigidity of the frame over time [8, 16].

This frequency of beam replacement is confirmed by studies [17, 18] that revealed cracks in the first 20 years of service life of a beam. After 25–50 years of service life, the number of beams with cracks increases up to a quarter. While substituting 25 years of service life into the linear model (Fig. 6), a damage rate of 24.8% is obtained for crane beams, which almost coincides with the data [17].

The analysis showed that service life of crane beams can be divided into conditionally permanent time periods: after up to 25 years of service life, the average damage rate of beams reaches 30% resulting in repairs and restoration, leading to a twofold reduction in the number of damaged structures [6]. According to the graph, such conditionally permanent time periods are about 20 years long. At the same time, with intensive crane operation, periods of repairs and replacement of crane beams are reduced to 5–10 years [9].

Discussion and Conclusion. The results of the study of correlations of damage and service life are based on the previously conducted and published studies by the author of the frequency of damage to structures of industrial buildings [19]. The rate of damage to steel columns of industrial buildings is higher than that of reinforced concrete. The intensity of damage to steel columns is described by an exponential dependence, while that of reinforced concrete columns is linear. The dependence "damage – service life" of reinforced concrete floors and coatings is approximated by a second-degree polynomial close to a linear dependence of 1% per year. The same linear damage is typical of steel trusses. Brick and reinforced concrete walls are damaged linearly depending on service life and with approximately equal intensity — 0.7% per year. Crane beams are the most damaged frame structures and are subject to periodic replacement after an average of 20 years of service life (a specific frequency depends on the operating mode of cranes). The damage rate of crane beams does not directly depend on service life of a building itself. The time trend has shown that as service life of a building increases, so does the intensity of damage to crane beams, which might be due to a decrease in the overall rigidity of the frame and wear of lifting equipment over time.

According to the results of the study of a sample of industrial buildings, the implicit features of damage accumulation have been identified. Thus, for widespread steel columns and coating trusses, in comparison with reinforced concrete ones, defects and damage were observed as early as at the initial stage of operation. Damage after 0 to 10 years of service life for columns is 10% of the total number, damage to the coating trusses is 19–32% of the total number. What is more, the damage to the steel columns of buildings of less than10 years of service life turned out to be greater than for those after 10–20 years of service life. It is obvious that defects and damage at the initial stage of operation are due to the mistakes made during the QMS and acceptance control. Metal structures at the stages of storage, installation, and engineering systems are damaged and accumulate defects (shelf bends, damage to protective primer, fire protection, defects in bolted and welded joints) that are not eliminated in a timely manner before as object is put into operation. The analysis of the inspections and examinations has identified the impact of the quality of the foundations for columns on a building frame — deviations cause mismatches in holes, gaps in connected elements of a metal frame that appear at the assembly stage due to the lack of recommendations developed in project documentation for eliminating them, no additional flat and wedge-shaped gaskets and elongated bolts in standard kits.

In order to increase the period of safe operation and intervals between repairs for newly erected industrial buildings with a metal frame, it is essential to provide measures in advance or as part of maintenance for reducing the number of defects and damage. It is recommended that a risk-based approach is applied to determining such measures considering forecast likelihood of mistakes, frequency of defects and damage as well as restoration costs [20].

The resulting mathematical models of "damage-service life" can be employed in optimizing maintenance, planning periodic inspections, ongoing and major repairs of buildings as well as in developing a strategy for enterprises to replace fixed industrial assets.

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