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EXPERIMENTAL STUDIES OF REINFORCED CONCRETE BEAMS WITH POST-TENSIONED ROPES

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Abstract. The current state of a significant part of the building stock is characterized by a gradual decrease in the operational reliability of reinforced concrete structures, which is due to the combined effect of physical and mechanical, environmental factors, as well as a result of military operations. Long-term operation, the influence of aggressive environments, exceeding the design loads, as well as design errors and military operations lead to the development of defects and damage, which in some cases go into the emergency stage. Particularly critical is the disruption of the operation of beam elements, since they determine the stiffness and load-bearing characteristics of the structural system as a whole. Under such conditions, there is a need to implement effective technical solutions aimed at restoring the load-bearing capacity.

The paper considers an approach to strengthening reinforced concrete beams using post-tensioned ropes. Unlike traditional methods based on increasing the cross-section or introducing additional elements, the proposed technology allows for the implementation of the effect of pre-compression in the stretched zone without a significant increase in the mass and dimensions of the structure, which is fundamentally important when working with existing and emergency facilities.

The experimental part of the study is based on a comparative analysis of two series single-span beams:

- ✓ control samples without amplification but with a different manufacturing method
- ✓ equipped with a post-tensioning system, which are reinforced using various methods.

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In this case, the reinforced beams include both samples in which the design solutions provided for the possibility of tension at the manufacturing stage, and elements whose reinforcement was performed after the concrete gained strength by arranging holes, installing anchor devices and subsequent monolithic construction. This approach allows us to assess the effectiveness of the technology both for new structures and in the conditions of reconstruction of existing elements.

During the tests, the dependences between the level of applied load and the magnitude of displacements were investigated, and the features of crack development and stiffness changes at different stages of operation were analyzed. The organization of the experiment provided for phased loading with continuous fixation of parameters, which provided the possibility of detailed analysis of the behavior of structures.

The practical significance of the study lies in using the obtained data to improve calculation

models and recommendations for the use of post-tensioned systems in reconstruction.

Keywords: reinforcement; prestressing; post-tension; ropes; experiment

INTRODUCTION

Ensuring the reliability and safety of the operation of buildings and structures is one of the key tasks of modern construction science and engineering practice. During long-term operation, reinforced concrete structures undergo a gradual decrease in their physical and mechanical characteristics, which leads to a deterioration in their bearing capacity, stiffness and crack resistance. A significant part of the existing building stock, formed mainly in the second half of the twentieth century, currently operates in conditions that differ from the initially established design assumptions, which leads to an increased risk of defects and damage.

The main causes of structural degradation are the complex action of operational and environmental factors, in particular, corrosion of reinforcement, carbonization of concrete, the influence of cyclic and long-term loads, as well as exceeding permissible operational parameters. Taken together, these phenomena lead to the accumulation of damage, which can turn into a pre-accident or emergency state. Beam elements are especially vulnerable, which play a decisive role in the transfer of loads and the formation of spatial rigidity of structural systems.

A separate and extremely relevant factor that significantly affects the technical condition of buildings and structures in Ukraine is the consequences of military operations. Explosive loads, shock waves, local destruction and damage to load-bearing elements lead to a sharp decrease in their performance or complete loss of load-bearing capacity. Under such conditions, a significant number of emergency structures are formed, which are characterized by integrity violations, the development of cracks and dangerous deformations. This necessitates the development of effective engineering solutions that can provide operational strengthening and stabilization of the state of structures without full-scale reconstruction.

Traditional methods of restoration and reinforcement, based on increasing the cross-section or installing additional elements, do not always meet the requirements of speed and technological feasibility of work, especially in conditions of limited access or the need for urgent intervention. In addition, such methods are often accompanied by a significant increase in the mass of the structure and the complication of its operation.

In this context, technologies that allow for purposeful change of the stress-strain state of structures with minimal intervention in their geometry are of particular interest. One of the promising areas is the use of post-tensioned ropes, which provide the introduction of compressive forces into the stretched zones of elements. The use of post-tensioned ropes allows for effective reduction of the level of tensile stresses, limiting the development of cracks, reducing deflections and increasing the overall stiffness of structures.

An important advantage of this approach is that it can be applied not only to new elements, but also to existing structures, including damaged or emergency ones. This makes post-tensioning technology particularly relevant in post-disaster recovery conditions, in particular for structures damaged by military operations, where time is critical and the need to quickly restore the functionality of structures is essential.

Despite the existence of separate studies devoted to the use of prestressed elements in domestic practice [1…14], this direction remains underdeveloped and fragmentary. Most of the works are focused mainly on theoretical aspects or individual applied problems, which does not allow to form a generalized methodological basis for the widespread implementation of the technology. The lack of systematized experimental data and substantiated recommendations significantly limits the possibilities of applying post-tensioning in the practice of strengthening and reconstruction of reinforced concrete structures.

At the same time, in world engineering practice, post-tensioning technology has become widely used and has proven its effectiveness in various construction industries [15…22]. Accumulated international experience indicates the feasibility of its use both in new construction and in the restoration and strengthening of existing structures, which emphasizes the need for further development of this area in Ukraine.

This gap between international experience and national practice emphasizes the need not only to develop an experimental base, but also to integrate Ukrainian regulatory documents [23…25] with modern world standards [26]. Harmonization of requirements will ensure the effective implementation of post-tensioning technology and create conditions for increasing the reliability and durability of building structures in the processes of reconstruction and restoration.

Thus, conducting experimental studies aimed at assessing the effectiveness of using post-tensioned ropes to strengthen reinforced concrete beams is an important scientific and practical task. Of particular relevance is the study of the possibilities of using this technology for the operational strengthening of emergency structures, which will allow increasing the level of safety, ensuring the stabilization of their operation and creating the prerequisites for further operation or reconstruction.

EXPERIMENT ORGANIZATION

The methodological basis of this study is the approach developed and substantiated in the previous work [1], where the general principles of experimental research of reinforced concrete elements were formed, the main test parameters were determined and a scheme of the experiment organization was developed. Unlike the previous stage, in this work the specified methodology is specified and adapted taking into account the changed experimental program.

For experimental research, single-span reinforced concrete beams with a span of 1.9 m were used, which were divided into two series:

The first series of beams are beams made without reinforcement, but divided into 2 beams:

- ✓ B-1.1 beam is manufactured without anchor and ropes.
- ✓ B-1.2 beam is manufactured with pre-installed anchor and rope for reinforcement.

The second series consisted of beams that, after testing the first series, were reinforced by post-tensioning. Depending on the technology of installing the reinforcing elements, the following samples were distinguished:

- ✓ B-2.1 post-tensioned beam (B-1.1) reinforced using elements pre-installed at the manufacturing stage (ropes and anchors).
- ✓ B-2.2 post-tensioned beam (B-1.2) reinforced using elements installed at the stage of conducting the experiment.

All samples had the same geometric parameters and internal reinforcement scheme, which ensured the correctness of further comparative analysis. The volumes and characteristics of the test samples are given in Table 1.

The beams were manufactured under controlled conditions using concrete of strength class C20/25. After molding, the samples were aged in a controlled environment until the design strength was achieved. Additionally, tests were carried out on control concrete samples, namely three cubes measuring 100×100×100 mm, to determine the actual physical and mechanical characteristics of the material, which made it possible to specify the parameters of further analysis. In addition, tests were carried out on reinforcing steel to determine its actual strength and deformation characteristics, the results of which were taken into account during data processing.

Before the start of the tests, each beam underwent a visual inspection to identify possible defects that could affect the results of the study (see Fig. 1 and 2).

Table 1 Volumes and characteristics of the samples studied
Табл. 1 Обсяги та характеристика дослідних зразків

Series	Marking beams	Amount	Test scheme	Notes
1 (without post-tensioning)	B-1.1	1		The beam is manufactured without pre-reinforcement and post-tensioning technology see Fig. 1
	B-1.2	1		The beam is manufactured with pre-installed anchor and rope for reinforcement without post-tensioning see Fig. 2
2 (with post-tensioning)	B-2.1	1		Post-tensioning beam reinforced after testing the first series using elements pre-arranged at the manufacturing stage see Fig. 4
	B-2.2	1		Post-tensioning beam reinforced after testing the first series using elements pre-arranged directly at the experimental stage see Fig. 7

Fig. 1 Beam of the first series B-1.1.
Photo by: Vynokur V.
Рис. 1 Балка першої серії Б-1.1.
Автор фото: Винокур В.

Fig. 2 Beam of the second series B-2.2.
Photo by: Vynokur V.
Рис. 2 Балка другої серії Б-2.2.
Атор фото: Винокур В.

After that, the beams were installed on a stationary test stand with hinged-fixed and hinged-movable supports that simulate the operation of the structure in real operating conditions.

For each series of tests, separate test stands were organized, which are shown in Figures 3 and 4.

Fig. 3 First series test stand.
Photo by Vynokur V.
Рис. 3 Стенд випробування першої серії.
Автор фото: Винокур В.

Fig. 4 Second series test stand.
Photo by Vynokur V.
Рис. 4 Стенд випробування другої серії.
Автор фото: Винокур В.

The loading system was implemented using a hydraulic jack connected to an oil station, which provided smooth adjustment of the applied force. The loading scheme provided for the application of a concentrated force, which allowed reproducing the operating conditions of the beam during bending. The loading geometry and the location of the force application points are shown in Fig. 8 and 9.

Before the start of the tests, the hydraulic jack and pressure gauge were calibrated to ensure the accuracy of the applied forces and the reliability of the measurements (see Fig. 5).

The calibration was carried out using reference loading devices, which allowed us to establish the correspondence of the pressure gauge readings to the actual pressure values.

The displacements were measured using high-precision deflection indicators installed in the middle of the span. The measurement accuracy was up to 0.1 mm. In addition, deformations were monitored in characteristic zones (see Fig. 8 and 9), as well as the moments of crack formation and development were recorded.

The load was applied stepwise with a given step, which allowed to monitor in detail the change in the stress-strain state at each stage. The initial load levels were used to check the correct operation of the measuring system and to record the initial deformations. Further increase in the load was carried out until the limit state of the structure was reached or the bearing capacity was lost.

For beams of the second series, reinforced with post-tensioned ropes, it was assumed that tension would be created using hydraulic equipment, a photo of the implementation of which is shown in Fig. 6.

Fig. 5 Calibrating the hydraulic jack and pressure gauge.
Photo by: Vynokur V.
Рис. 5 Калібрування гідравлічного домкрату та манометру. Автор фото: Винокур В.

Fig. 6 Creating tension using a jack.
Photo by: Vynokur V.
Рис. 6 Створення натягу за допомогою домкрату. Автор фото: Винокур В.

In the second series of tests, individual beams were reinforced by installing anchor nodes and post-tensioned cables. The holes for the anchors and cables were made directly by the author of the study in the body of the beams in compliance with technological requirements (see Fig. 7), after which the anchors were fixed in concrete using a high-strength mixture.
This approach allowed us to recreate the real conditions of reconstruction and restoration of emergency structures, when reinforcement is performed on existing elements that are in operation.

During the tests, all controlled parameters were continuously recorded in real time. These included deflections, deformations, the level of applied load, and crack formation parameters. The obtained data were stored for further processing, construction of experimental relationships, and determination of characterristic stages of the structure's operation

Fig. 7 Fragment of a beam of the second series with installed anchors. Photo by: Vynokur V.
Рис. 7 Фрагмент балки другої серії з влаштованими анкерами. Автор фото: Винокур В.

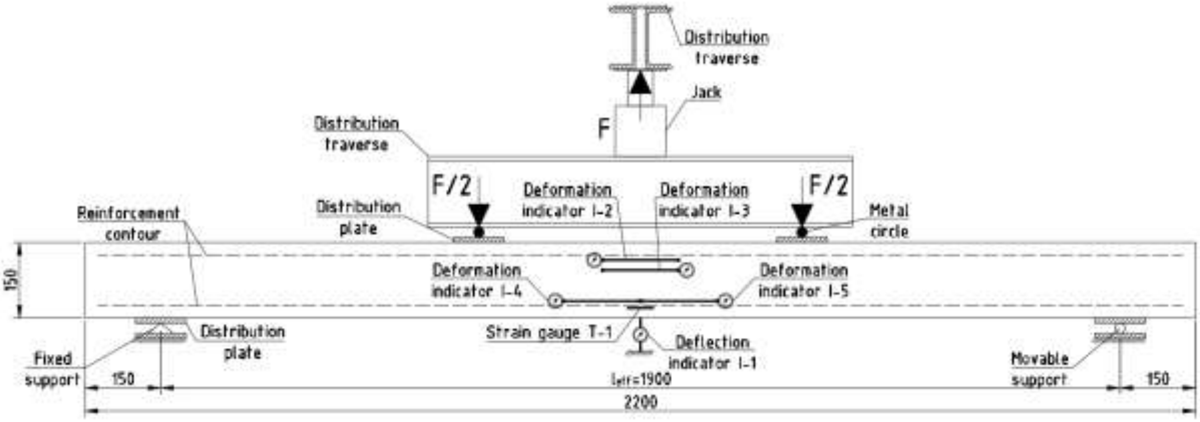

Fig. 8 Test scheme for beams B-1.1 and B-2.1 without post-tensioning technology
Рис. 8 Схема випробування балок Б-1.1 та Б-2.1 без технології постнапруження

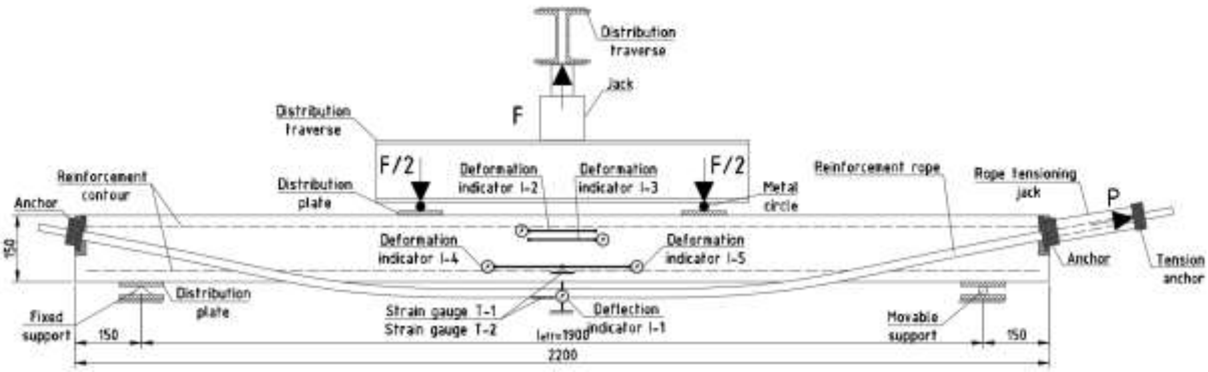

Fig. 9 Scheme of testing reinforced beams B-1.2 and B-2.2 using post-tensioning technology
Рис. 9 Схема випробування підсилених балок Б-1.2 та Б-2.2 за допомогою технології постнапруження

The proposed experimental research methodology provides high accuracy, repeatability and reliability of the results. This creates an opportunity for their further use in the development of computational models, as well as for comparison with the results of other studies in this field.

CONCLUSIONS

As a result of the research, a scientifically sound approach to the experimental study of reinforced concrete beams using post-tensioned ropes as a means of reinforcement was formed. The proposed methodology is based on the principle of comparative analysis of control and reinforced samples, which allows for objective assessment of the influence of post-tensioning on the stress-strain state of structures.

The developed experimental methodology provides a comprehensive approach to studying the behavior of beams under load, including stepwise loading, fixation of deformation parameters, crack formation control, and the possibility of implementing repeated loading cycles. This approach creates conditions for obtaining representative data and allows analyzing the operation of structures not only at the limit stages, but also in the range of operational loads.

A feature of the proposed methodology is the consideration of various scenarios for the application of post-tensioning technology, in particular for elements in which reinforcement is envisaged at the manufacturing stage, as well as for structures that are reinforced after commissioning. This expands the scope of the study and ensures its practical orientation.

Special attention is paid to the possibility of using post-tensioned ropes as an effective tool for strengthening structures that are in a pre-accident or emergency state. In the context of modern challenges, in particular, damage to buildings as a result of military actions, it is relevant to develop technologies that allow for rapid stabilization of the state of elements and ensure their further operation without the need for complete dismantling. The proposed approach meets these requirements due to the possibility of rapid implementation and minimal intervention in the existing structure.

The experimental data obtained within the framework of this work form an information basis for their further analytical processing, generalization and interpretation. On their basis, it is planned to perform an in-depth analysis of the patterns of deformation, crack formation and changes in the stiffness characteristics of reinforced elements, as well as to develop refined approaches to assessing the effectiveness of post-stressing.

The contribution of the work to the scientific sector of the construction industry consists in the development of methodological principles of experimental research of reinforced concrete elements and the formation of a basis for further analysis of the effectiveness of the use of post-tensioning. The practical value lies in creating prerequisites for improving engineering methods of reinforcement, adapting modern technologies to the conditions of domestic construction and harmonizing the regulatory framework with international standards.

In further research, it is advisable to expand the experimental base, generalize the obtained data, and develop calculation models that will allow a more complete assessment of the influence of post-stressing parameters on the operation of reinforced concrete structures.

ETHICAL DECLARATIONS

The authors have no relevant financial or non-financial interests to report.

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ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ ЗАЛІЗОБЕТОННИХ БАЛОК З ПОСТНАПРУЖЕНИМИ КАНАТАМИ

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Анотація. Сучасний стан значної частини будівельного фонду характеризується поступовим зниженням експлуатаційної надійності залізобетонних конструкцій, що обумовлено сукупною дією фізико-механічних, середовищних факторів а також в наслідок військових дій. Тривала експлуатація, вплив агресивних середовищ, перевищення розрахункових навантажень, а також помилки проєктування та воєнні дії призводять до розвитку дефектів і пошкоджень, які у ряді випадків переходять у стадію аварійного стану. Особливо критичним є порушення роботи балкових елементів, оскільки саме вони визначають жорсткісні та несучі характеристики конструктивної системи в цілому. За таких умов постає необхідність впровадження ефективних технічних рішень, спрямованих на відновлення несучої здатності.

У роботі розглянуто підхід до підсилення залізобетонних балок із застосуванням постнапружених канатів. На відміну від традиційних методів, що базуються на збільшенні перерізу або введенні додаткових елементів, запропонована технологія дозволяє реалізувати ефект попереднього стиску у розтягнутій зоні без суттєвого збільшення маси та габаритів конструкції, що є принципово важливим при роботі з існуючими та аварійними об’єктами.

Експериментальна частина дослідження побудована на порівняльному аналізі двох серій однопролітних балок:

- ✓ контрольних зразків без підсилення, але з іншим методом виготовлення
- ✓ оснащених системою постнапруження, які підсилюються різними методами.

При цьому підсилені балки включають як зразки, у яких конструктивні рішення передбачали можливість натягу на стадії виготовлення, так і елементи, підсилення яких виконувалося після набору міцності бетону шляхом улаштування отворів, монтажу анкерних пристроїв і подальшого замонолічування. Такий підхід дозволяє оцінити ефективність технології як для нових конструкцій, так і в умовах реконструкції існуючих елементів.

У процесі випробувань досліджено залежності між рівнем прикладеного навантаження та величинами переміщень, а також проаналізовано особливості розвитку тріщин і зміни жорсткості на різних стадіях роботи. Організація експерименту передбачала поетапне навантаження із безперервною фіксацією параметрів, що забезпечило можливість детального аналізу поведінки конструкцій.

Практична значущість дослідження полягає у використанні отриманих даних для вдосконалення розрахункових моделей та рекомендацій щодо застосування постнапружених систем у реконструкції.

Ключові слова: підсилення, попереднє напруження, постнапруження, канати, експеримент.

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