

## BRIDGES AND TUNNELS: THEORY, RESEARCH, PRACTICE

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### INVESTIGATION OF THE INFLUENCE OF BRIDGE SPAN LENGTH ON INCREASING THE BEARING CAPACITY OF REINFORCED CONCRETE BRIDGE BEAMS REINFORCED WITH EXTERNAL PRE-STRESSED REINFORCEMENT

**Purpose.** The purpose of the study is to establish a quantitative relationship between the span length of existing reinforced concrete bridge girders (typical beams of type 56, designed for N-30 load) and the relative efficiency of reinforcement with external prestressed reinforcement. The ultimate goal is to ensure safe operation under modern load classes AK-15/NK-100. **Methodology.** An analysis of the lining stress-strain state for typical beams type 56 span lengths: 11.36 m, 16.76 m and 22.16 m. Beam models were built based on real geometric dimensions using professional calculation software LIRA SAPR. This approach made it possible to simulate the spatial behavior of the structure and to account for the actual boundary conditions and applied loads. Calculations were performed for beams with different span lengths. To ensure the load-bearing capacity of the standard beam type commonly used in existing highway bridges in Ukraine under modern traffic loads, the required additional area of reinforcement was determined using the corresponding design formula. **Findings.** The numerical analysis confirmed that the application of external pre-stressed reinforcement ensures the necessary bearing capacity for all span structures. It was established that although the absolute increase in bearing capacity significantly grows with the increase in span length, the relative efficiency of strengthening substantially decreases simultaneously: the rate of increase in the reinforcement effect slows down on longer beams. **Originality.** The originality of the study consists of the obtained results of numerical analysis that established and quantified the functional dependence between span length and the relative efficiency of External Pre-Stressed Reinforcement, and introduced the novel criteria for structural diagnosis. **Practical value.** The study provides a scientifically verified engineering algorithm for the mass modernization of typical bridge beams, ensuring a cost-effective path to restoring safety, durability, and compliance with the AK-15 load standard.

**Keywords:** load-bearing capacity; external prestressed reinforcement; bridge beams; finite element method; crack resistance; transport loads; durability; strengthening; reconstruction; stress-strain state

#### Introduction

It is generally accepted that the service life of bridge structures is about 100 years, as their most durable components are piers and foundations. However, the operational lifespan of superstructures is significantly shorter approximately 40 years especially in the absence of systematic maintenance and repair. The vast majority of bridges in Ukraine are reinforced concrete. On public roads of national importance, their share reaches nearly 94 % (Каськів, Панібратець, Степанов, Грінів, & Чайковська, 2024).

Most of the span structures in Ukraine's bridge

stock, including standard beams of Type 56, were designed according to outdated design load standards such as N-30 and NK-80 (Сінь, Горбачевська, Салійчук, & Кваша, 2023; Mirosnyk, Tao, Du, & Ivanchenko, 2025). These loads are considerably lower than current traffic demands. Over the past decades, the increase in traffic intensity and the emergence of large and heavy vehicles have required upgrading bridges to modern load classes, namely AK-15 and NK-100 (ДБН В.2.3-14:2006, 2006; ДБН В.2.3-22:2009, 2009). This leads to accelerated physical deterioration, crack formation, and a reduction in load-bearing capacity. Consequently, a significant por-

tion of the bridge's life cycle occurs under overloaded conditions, which results in premature degradation and excessive repair costs (Лучко, 2023).

A review of international scientific publications shows that most recent studies focus on strengthening methods using External Prestressing (Suntharavadeivel, & Aravinthan, 2005). This method has been widely investigated because it effectively enhances the structural bearing capacity, reduces deflections, and prevents crack formation (Попович, Миронюк, & Борщов, 2005). Research highlights that external prestressing is particularly effective for aging bridges originally designed for lower loads, as it helps restore deformation characteristics and improve fatigue resistance. For instance, an experimental study published in MDPI (Park, H. B., Park, J. S., Kang, & Jung, 2018; Kim, S. H., Park, Jung, Kim, T. K., & Park, 2021) demonstrated the efficiency of this technique on a real bridge that had been in service for more than 45 years.

However, despite extensive research on external prestressing, the influence of span length on the efficiency of reinforcement and the resulting increase in bearing capacity remains insufficiently studied. The geometric characteristics of the span structure, particularly its length, have a direct impact on stress redistribution, bending moments, and the effectiveness of external tendons. Therefore, understanding this relationship is essential for optimizing strengthening strategies for bridges of different configurations.

### Purpose

The purpose of this study is to establish a quantitative relationship between the span length of reinforced concrete bridge beams and the effectiveness of increasing their load-bearing capacity through external prestressed reinforcement, with respect to bending moment, in order to ensure safe operation under modern standard loads, particularly AK-15 and NK-100.

### Methodology

To calculate the internal forces in the elements of the span structure, a 3D model of the reinforced concrete beam was developed in the LIRA-SAPR software (Figure 1), and its corresponding computational scheme was created (Figure 2).

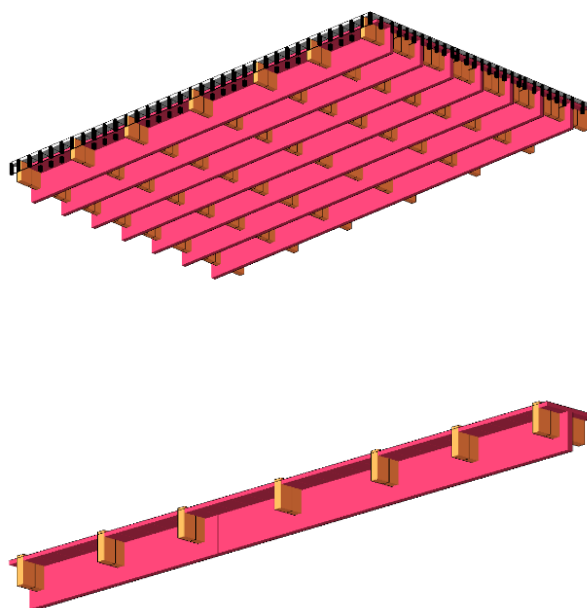


Figure 1. 3D model in PC LIRA-SAPR

This approach made it possible to simulate the spatial behavior of the structure and to account for the actual boundary conditions and applied loads.

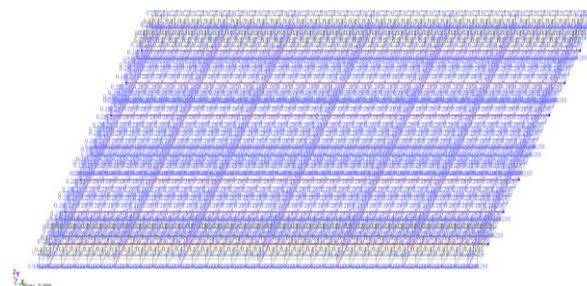


Figure 2. Calculation scheme in PC LIRA-SAPR

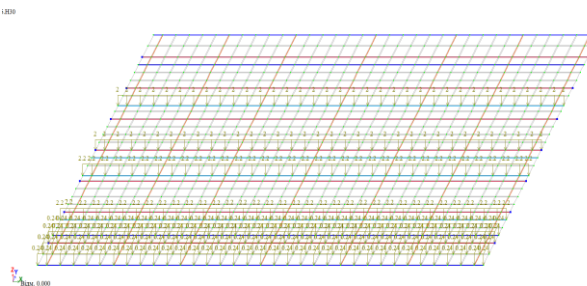


Figure 3. Load from H-30 to LIRA-SAPR

Calculations were performed for beams with different span lengths. To ensure the load-bearing capacity of the standard beam type commonly used in existing highway bridges in Ukraine under modern traffic loads, the required additional area of

reinforcement was determined using the corresponding design formula (P B.3.2-03450778-832:2013, 2013; P B.3.2-218-03450778-741:2008, 2013). To achieve the necessary bearing capacity in accordance with current design standards, a structural analysis was carried out. The results showed that, to strengthen the beam using conventional reinforcement, it is necessary to install two bars with a diameter of 32 mm. This solution compensates for the deficiency in strength identified in typical beams of this series.

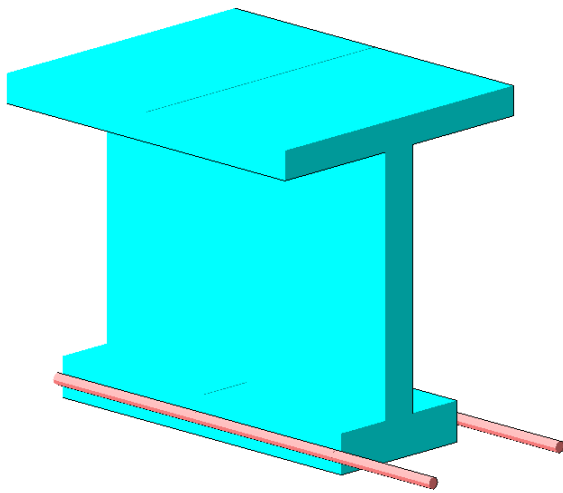


Figure 4. Calculation model of the cross-section of a typical span beam (Type 56) reinforced with two conventional reinforcement bars

After the proposed reinforcement, the load-bearing capacity of the beam is ensured in accordance with the AK-15 load class for beams of all lengths (11.36 m, 16.76 m, and 22.16 m). The load-bearing capacity of the cross-section is determined using the following formula:

$$M_{ultimate} = \begin{cases} R_b \cdot b_{f1} \cdot x \cdot (h_0 - \frac{x}{2}) & \text{if } x < h_{f1} \\ R_b \cdot (b_{f1} - b) \cdot h_{f1} \cdot (h_0 - 0.5 \cdot h_{f1}) + \\ + R_b \cdot b \cdot x \cdot (h_0 - \frac{x}{2}) \end{cases}$$

where  $M_{ultimate}$  – the ultimate bending moment of the beam cross-section, which defines its load-bearing capacity;  $R_b$  – the design compressive strength of concrete, a strength characteristic that includes reliability factors depending on the concrete class;  $b$  – the width of the beam web;  $h_0$  – the effective depth of the cross-section, defined as the distance from the compressed edge to the centroid of the tensile reinforcement;  $b_{f1}$  – the width of the flange (upper part of the beam);  $h_{f1}$  – the thickness of the flange (upper part of the beam);  $x$  – the height of the neutral axis measured from the most compressed edge of the cross-section.

Thus, the total ultimate bending moment of resistance of the strengthened beam  $M_{ep.noc.}$  was determined as follows:

$$M_{strengthened} = M_{ultimate} + M_{munoee}$$

### Findings

The strengthening effect is calculated as the increase in load-bearing capacity in terms of bending moment resulting from the application of prestressed tendons.

The effect of strengthening is measured as the difference between the ultimate load-bearing capacity of the strengthened beam and its initial capacity according to the typical design (table 1, Figure 5).

Table 1

Calculation results for beams of different lengths

Beam length (L)	Load-bearing capacity according to the typical design ( $M_{typical}$ )	Load-bearing capacity of the strengthened beam ( $M_{strengthened}$ )	Strengthening effect
11,36 m	67 tf·m	104 tf·m	104-67=37
16,76 m	141 tf·m	215 tf·m	215-141=74
22,16 m	194 tf·m	288 tf·m	288-194=94

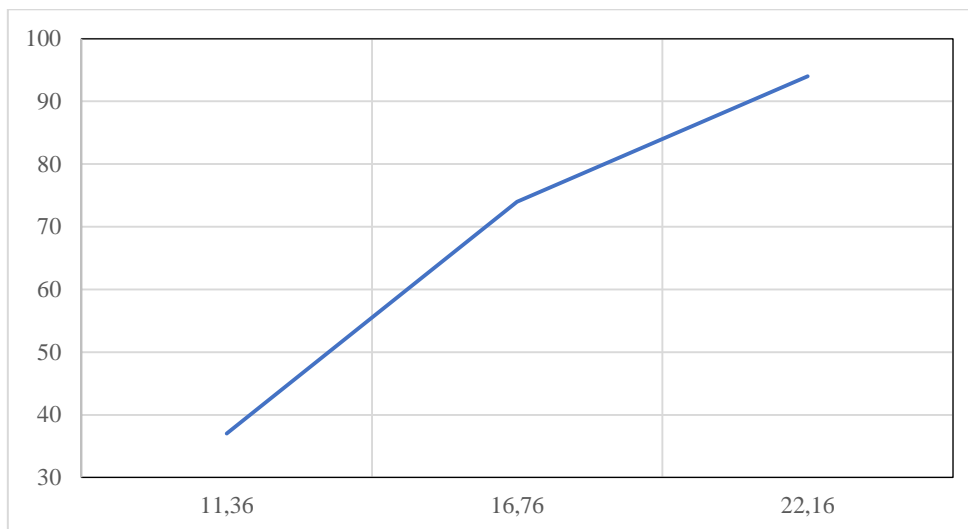


Figure 5. Dependence of the strengthening effect on beam length

The analysis of the obtained results demonstrates that the absolute deficit of load-bearing capacity  $\Delta M$  (the difference between the bending moment required to resist the current design loads and the bending moment that a typical beam can withstand) increases with the growth of span. Strengthening provides a noticeable absolute gain in bending resistance, although the rate of this increase slows down for longer spans. To enable an objective assessment, a deficit coefficient  $K_1$  (analogous to the Load Rating Factor) was introduced. This coefficient converts the absolute deficit into a relative value, allowing a uniform comparison of beams of different lengths. The analysis confirmed that the long-span beam  $L=22.16$  m (with  $K_1=0.371$ ) is at a critical strength deficit level (exceeding 35 %), which forms the basis for assessing the technical condition and prioritizing urgent strengthening measures.

$$K_1 = \frac{\Delta M}{M_{\text{typical}}}$$

To interpret the proposed deficiency coefficient  $K_1$ , a conditional scale of values was introduced to represent structural safety and serviceability levels. The selected threshold values (0.20 and 0.35) are based on engineering reasoning and align with approaches commonly used in structural assessment practice. A deficiency up to 20 % ( $K_1 < 0.2$ ) is considered acceptable, corresponding to typical safety factors adopted in design standards. Values within  $0.2 \leq K_1 \leq 0.35$  indicate a noticeable loss of capacity, associated with increased risk of cracking and

excessive deflection under heavy traffic. When  $K_1 > 0.35$ , the structure has lost more than one-third of its required capacity, which is regarded as a critical condition demanding immediate strengthening. This classification is methodological and serves to enhance the interpretability of analytical results, complementing existing standards and providing a practical diagnostic tool for evaluating the technical condition and prioritizing bridge strengthening measures.

For a more detailed assessment, a sensitivity coefficient  $K_2$  (length sensitivity coefficient) was introduced to evaluate the rate of increase in the deficit of load-bearing capacity per unit length. The analysis demonstrated that  $K_2$  consistently grows with increasing span length (from approximately 2.0 tf·m/m to 3.2 tf·m/m), confirming that longer span structures are more sensitive to overloads and should be considered a top priority for strengthening.

$$K_2 = \frac{\Delta M}{L}$$

Thus, coefficient  $K_2$  refines the assessment provided by coefficient  $K_1$  and enables a comparative analysis of span structures of different lengths in terms of their susceptibility to overloading. The use of this parameter makes it possible not only to quantitatively evaluate the dependence of the stress-strain state on the geometric characteristics of the beam but also to ensure a consistent comparison of beams of various lengths regarding their sensitivity to overloads.

### Originality and practical value

The originality of the study consists in the obtained results of numerical analysis for reinforced concrete span beams, which made it possible to establish and quantify the functional dependence between the span length and the relative efficiency of the External Pre-Stressed Reinforcement method, as well as to introduce new diagnostic criteria for assessing structural performance and the necessity of strengthening interventions.

The practical value lies in the development of a scientifically substantiated engineering algorithm for the large-scale modernization of standard bridge beams in Ukraine's transport infrastructure, which ensures a cost-effective and technically reliable way to restore load-bearing capacity, extend service life, and achieve compliance with the AK-15 load class standard.

### Conclusions

The numerical analysis performed for dead weight and modern moving loads (AK-15/NK-100) allowed for finding out the parameters of the stress-strain state and evaluating the overall strength.

The study proved that the application of external pre-stressed reinforcement (four 12.5 mm strands) ensures the necessary bearing capacity for all analyzed span structures. It was established that the absolute increase in bearing capacity (the strengthening effect) remains significant for all spans and substantially grows with the beam length. This is explained by the fact that the bending moment from external loads that needs to be compensated grows proportionally with the span.

However, a key finding is that while the absolute effect increases, the relative efficiency of strengthening significantly decreases with increasing beam length. Concurrently, it was established that the rate of increase in the effect slows down on longer spans. Based on the determined parameters, the overall strength and stability of the strengthened beams were evaluated, and recommendations for prioritizing reconstruction works were provided, focusing on maximizing the structural return on investment across the bridge network.

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## ДОСЛІДЖЕННЯ ВПЛИВУ ДОВЖИНИ ПРОГОНОВОЇ БУДОВИ НА ПІДВИЩЕННЯ НЕСНОЇ ЗДАТНОСТІ ЗАЛІЗОБЕТОННИХ МОСТОВИХ БАЛОК ПРИ ПІДСИЛЕННІ ЗОВНІШНІМ ПОПЕРЕДНЬО НАПРУЖЕНИМ АРМУВАННЯМ

**Мета.** Метою дослідження є встановлення кількісної залежності між довжиною прогону існуючих залізобетонних балок мостів (типові балки серії Вип. 56, спроектовані під навантаження Н-30) та відносною ефективністю їх підсилення методом зовнішнього попереднього напруженого армування. Кінцева мета полягає у забезпеченні безпечної експлуатації споруд за сучасних класів навантаження АК-15/НК-100. **Методика.** Проведено аналіз напружено-деформованого стану типових балок серії Вип. 56 довжиною 11,36 м, 16,76 м та 22,16 м. Моделі балок були побудовані на основі реальних геометричних розмірів із використанням професійного розрахункового програмного комплексу LIRA-SAPR. Такий підхід дозволив змодельовувати просторову поведінку конструкції та врахувати фактичні граничні умови та прикладені навантаження. Розрахунки проводилися для балок з різною довжиною прольоту. Для забезпечення несучої здатності стандартного типу балки, що зазвичай використовується в існуючих автомобільних мостах України, за сучасних транспортних навантажень, необхідну додаткову площу армування визначали за відповідною розрахунковою формулою. **Результати.** Чисельний аналіз підтвердив, що застосування зовнішнього попереднього напруженого армування забезпечує необхідну несучу здатність для всіх розглянутих прогонових будов. Встановлено, що хоча абсолютне зростання несучої здатності істотно збільшується зі збільшенням довжини прогону, відносна ефективність підсилення водночас помітно знижується: зі збільшенням довжини балки темпи приросту ефекту від підсилення сповільнюються. **Наукова новизна.** Наукова новизна дослідження полягає в отриманих результатах чисельного аналізу, які дозволили встановити та кількісно оцінити функціональну залежність між довжиною прогону та відносною ефективністю методу зовнішнього попереднього напруження, а також у введенні нових критеріїв для структурної діагностики. **Практична значимість.** Дослідження пропонує науково обґрунтований інженерний алгоритм для масової модернізації типових мостових балок, що забезпечує економічно ефективний шлях відновлення безпеки, довговічності та відповідності споруд вимогам класу навантаження АК-15.

**Ключові слова:** довговічність; залізобетонна конструкція; підсилення; попереднє напруження; міст; моделювання; напружено-деформований стан; несуча здатність; реконструкція; транспортне навантаження; метод скінченних елементів

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