



DOI: 10.17512/bozpe.2026.15.03

**Construction of optimized energy potential**  
Budownictwo o zoptymalizowanym potencjale energetycznym

ISSN 2299-8535 e-ISSN 2544-963X



## Finite element modelling and analysis of a reinforced concrete beam bridge structure

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**Abstract:** This article presents a numerical study of a reinforced concrete beam-and-slab bridge span carried out using the finite element method (FEM). The analysed span consists of a slab and longitudinal ribs, with geometry and reinforcement based on a previously tested prototype. The ribs are reinforced longitudinally from 12 mm to 20 mm bars in five samples and transversely with 5 mm stirrups at 100 mm spacing, while the slab contains a 5 mm bar mesh with 50 mm spacing in both directions. A three-dimensional nonlinear FEM model was created, including material nonlinearity of concrete and reinforcing steel and realistic boundary conditions. The bridge span was analysed under static loads from 10.8 kN up to an ultimate load of 36 kN, and the results were compared with available experimental data. Stress and strain distributions, load-strain relationships, crack patterns and mid-span deflections were obtained for several configurations with different diameters of tensile reinforcement. The study shows how a gradual reduction of reinforcement diameter from 20 mm to 12 mm affects stiffness, strain levels and the serviceability limit state of the span, and demonstrates the potential of FEM for assessing the behaviour and safety of existing or reconstructed bridge structures.

**Keywords:** finite element method, non-linear calculation, reinforced concrete beams, stressed deformed state, concrete bridge structures

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Please, quote this article as follows:

Krasnitskyi, P., Blikharskyi, Y. & Selejdak, J. (2026) Finite element modelling and analysis of a reinforced concrete beam bridge structure. *Construction of Optimized Energy Potential (CoOEP)*, 15, 23-31. DOI: 10.17512/bozpe.2026.15.03

### Introduction

Bridge structures are critical elements of transport infrastructure, and their large-scale destruction during the war in Ukraine has made their rapid restoration

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a national priority. Accurate assessment of strength and durability can be achieved using modern numerical approaches, in particular **nonlinear finite element modeling**. In this study, FEM is applied to model reinforced concrete beams with different reinforcement diameters in order to evaluate their influence on structural behaviour. The obtained results form a basis for refining design methods and improving the reliability of bridge structures under current operating conditions.

The bridge industry is undergoing significant transformations due to the rapid development of structural materials and design methods. The emergence of high-strength concretes and advanced composite materials opens broad prospects for creating more reliable and durable bridge structures (Lantsoght, 2022). Modern bridges are no longer purely engineering objects; they increasingly serve as architectural landmarks that are harmoniously integrated into the surrounding environment (Gardner et al., 2020). At the same time, the integration of renewable energy sources, such as solar panels or wind turbines, into bridge structures is becoming an important trend that supports sustainable development (Hernández et al., 2015). The growing traffic intensity and the appearance of heavier vehicles require bridges with increased load-carrying capacity and reliability, which makes the issues of their design, rehabilitation and strengthening particularly relevant (Performance of concrete segmental ..., 2001). Dynamic effects caused by road surface irregularities and vehicle-bridge interaction also have a significant influence on the performance and service life of bridges (Schultz et al., 2022). These factors highlight the need for methods that can realistically represent the stress-strain state of bridge structures under operational loads.

Compared with traditional monitoring and inspection methods, finite element analysis allows for a substantial reduction in time and labour costs while providing detailed information on the internal forces and strains in structural members. Numerical modelling enables engineers to simulate the behaviour of bridges under different loading scenarios, including abnormal and extreme events, and to predict the effect of deterioration on structural performance (Harris et al., 2016; Karimpour et al., 2021). In particular, FE models are widely used for load rating, serviceability assessment and verification of strengthening schemes. In recent years special attention has been paid to the calibration and validation of FEM models using experimental field data. Growing traffic flow and increasing vehicle weight impose additional requirements on the strength, durability and serviceability of bridge structures (Colombani & Andrawes, 2022; Ding et al., 2012). To meet these challenges, advanced numerical methods are used, among which the finite element method stands out, as it can significantly improve the accuracy of predicting the behaviour of bridges (Dong et al., 2020; Karimpour et al., 2021). In recent years, particular attention has been paid to validating FEM models using experimental field data. Methods have been developed for updating full-scale numerical bridge models based on field test results (Ding et al., 2012; Dong et al., 2020). For example, the static and dynamic characteristics of existing bridge structures have been effectively assessed by calibrating FEM models using historical measurement data, which has made it possible to verify the compliance of structures with modern design standards (Liu et al., 2016; Ribeiro-Carvalho et al., 2021; Tran-Ngoc et al., 2018).

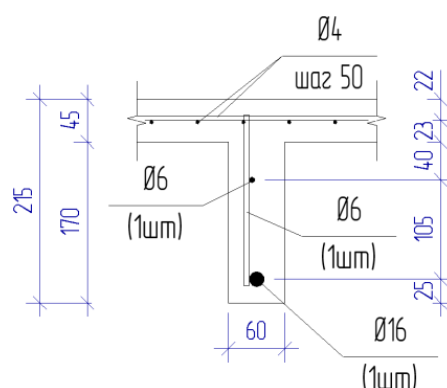
For more accurate and efficient calibration of numerical models of bridge structures, researchers actively use optimisation methods such as genetic algorithms (GA) and particle swarm optimisation (PSO) (Alkayem et al., 2018; Reynders et al., 2010; Zoltowski et al., 2022). These approaches have been implemented in combination with various FEM-based software packages, including ANSYS, SAP2000, ABAQUS and SOFiSTiK (Figueiredo et al., 2019; Jang & Smyth, 2017; Schemmel et al., 2020). A successful example of using SOFiSTiK is a pedestrian drawbridge over the Motława River in Gdańsk, where numerical models, calibrated with real test data, demonstrated high efficiency (Zoltowski et al., 2022).

Particular attention should be paid to studies that combine the MATLAB mathematical environment with ANSYS, SAP2000 and ABAQUS software. Such integration significantly simplifies automated calibration procedures for numerical models and increases both the accuracy and speed of calculations (Figueiredo et al., 2019; Jang & Smyth, 2017; Schemmel et al., 2020).

It is also relevant to integrate geometric parameters and physical-mechanical properties into a single parametric FEM model that takes into account the specifics of modern regulatory requirements and ensures effective implementation of design and reconstruction tasks for bridges (Brózda et al., 2017; Dinh-Cong et al., 2020; Ndong et al., 2019; Wu et al., 2017). Recent studies have proposed the use of intelligent sensor systems, which significantly improve the quality of updating numerical models based on historical field data and allow a rapid response to structural damage (Dinh-Cong et al., 2020; Korus et al., 2021; Martín-Sanz et al., 2019; Ndong et al., 2019; Wu et al., 2017). In Ukrainian practice, the finite element method is widely implemented in structural analysis software such as LIRA-SAPR, which is well adapted to domestic design codes. In Klymenko & Hlibotskyi (2024), methods for assessing residual bearing capacity are investigated using LIRA-SAPR. In Azizov et al. (2024), a static analysis of a caisson slab before cracking was performed to understand the origin of cracks in bridge beams. In Krasnitskyi & Lobodanov (2024); Kirichenko & Yesvandzhyla (2024); Vavruš & Koteš (2019), methodologies for analysing damaged reinforced concrete beams were developed by comparing results obtained in LIRA-SAPR with those from other FEM software packages. In the present study we also use LIRA-SAPR as a computational tool, but the focus is placed on the finite element method itself and on the resulting stress-strain state of the analysed beams rather than on the software brand.

## 1. Method of experimental research of concrete samples

In order to create a finite element model using FE No. 236 for concrete and FE No. 210 for reinforcement with a finite element size of  $25 \text{ mm} \times 25 \text{ mm} \times 25 \text{ mm}$  in the LIRA-SAPR environment, a number of sequential steps are required. The initial data for the reinforced concrete beam are specified in Figure 1 and in Table 1. All figures and tables used in the article are based on the authors' own drawings and calculations.

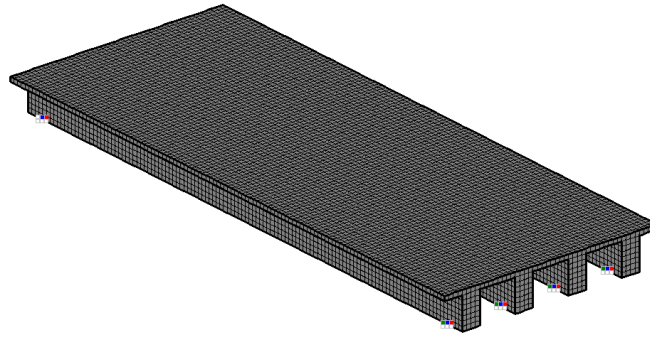


**Fig. 1.** Structural diagram of the beam (*own research*)

**Table 1.** Properties of materials specified in the calculation model of the beam (*own research*)

Material	Material properties	Value
Concrete	Density	2500 kg/m <sup>3</sup>
	Young's modulus	4000 MPa
	Poisson's ratio	0.2
	Tensile ultimate strength	2.5 MPa
	Compressive ultimate strength	27.5 MPa
Reinforcement A500	Density	7850 kg/m <sup>3</sup>
	Young's modulus	200 000 MPa
	Poisson's ratio	0.2
	Tangent modulus	20
	Tensile ultimate strength	500 MPa
	Compressive ultimate strength	0 MPa

In the FEM model, the slab-ribbed beam was represented by 3D finite element No. 236, to which the main concrete and reinforcement properties, including nonlinear behaviour under load, were assigned. To represent reinforcement more precisely, spatial bar element No. 210 was used, allowing the steel grade, bar diameter and nonlinear material response to be defined. All modelling parameters are summarised in Table 1. The beam was then restrained according to design assumptions by setting boundary conditions that reflect the actual support conditions and load application in line with regulatory requirements. Figure 2 illustrates the created reinforced concrete girder model. For the numerical study, five design schemes were prepared: the reference beam B-1 and beams B-2 to B-5, in which the diameter of the tensile reinforcement was varied. The analysis results for the full design load (100%) are presented in Table 2, showing the effect of reinforcement variation on structural response in terms of strains in concrete and in reinforcement.



**Fig. 2.** FE model of monolithic reinforced concrete beam (*own research*)

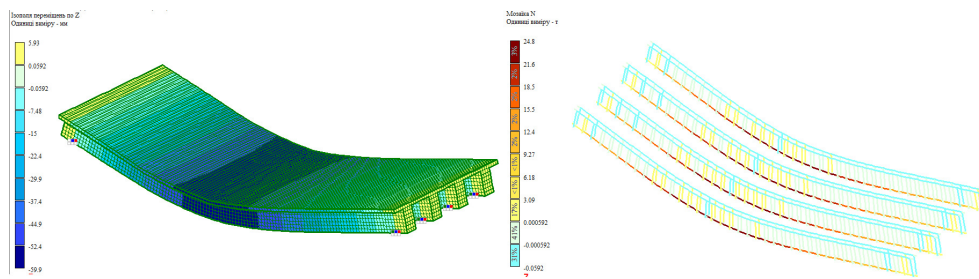
**Table 1.** Configuration of numerical models (*own research*)

Marking	The initial diameter of rebar	Diameter of rebar after change	Value of concrete strain in the original sample [%]	Concrete strain values in next samples [%]	Percentage deviation [%]	The value of reinforcement strain in the original sample [%]	The value of reinforcement strain in next samples [%]	Percentage deviation [%]
B-1	Ø 20	Ø 20	0.12	–	–	0.87	–	–
B-2		Ø 18		0.127	5%		0.96	10%
B-3		Ø 16		0.129	6%		1.02	17%
B-4		Ø 14		0.131	7%		1.14	30%
B-5		Ø 12		0.136	9%		1.22	40%

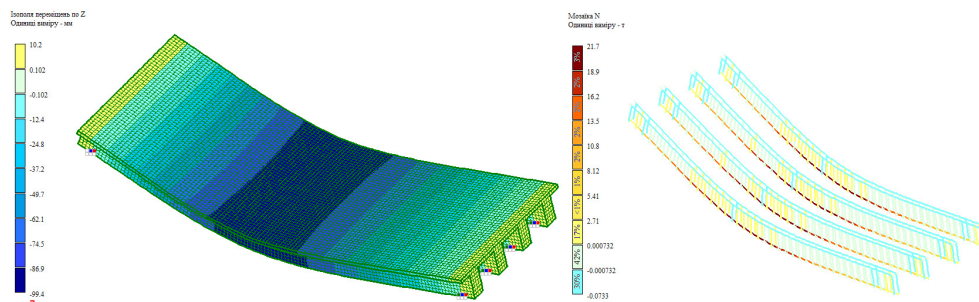
For the full design load considered here, the calculated strains in concrete and reinforcement remain below the ultimate strain values recommended by design codes; therefore, in all cases the state of the beam corresponds to the serviceability limit state (SLS). In this study, exhaustion of bearing capacity (ultimate limit state, ULS) would be associated with reaching the ultimate compressive strain of concrete or the ultimate tensile strain of reinforcement, or with loss of equilibrium of the system, none of which occurs within the analysed load range.

## 2. Results of experimental research on concrete samples

Analysing the results of the calculations for the five types of beams makes it possible to observe how a reduction in reinforcement diameter influences the bearing capacity of a reinforced concrete beam through changes in the behaviour of both the concrete and reinforcement. Table 2 shows how changes in the diameter of the tensile reinforcement affect the strains and provides comparative values for the calculated strains in the concrete and reinforcement. The relative differences range from 5% to 9% for the concrete and from 10% to 40% for reinforcement when compared with the reference beam B-1.



**Fig. 3.** The value of deformations of concrete and reinforcement for the experimental sample B-1 (*own research*)



**Fig. 4.** The value of deformations of concrete and reinforcement for the experimental sample B-4 (*own research*)

When the load level remains constant, the strain in the reinforcement changes noticeably as the bar diameter decreases from  $\text{Ø}20$  mm to  $\text{Ø}12$  mm. In the concrete, the maximum increase in strain reaches about 9 % in the zone of the maximum bending moment, while the reinforcement shows an even larger increase of about 13 % when the bar diameter is reduced from  $\text{Ø}18$  mm to  $\text{Ø}16$  mm, indicating stress redistribution in this region. Reducing bar diameter not only affects the numerical values of strain but also alters the pattern of stress distribution, as can be seen in Figures 3 and 4, particularly in the most highly stressed concrete sections. A decrease in reinforcement size also reduces the overall stiffness and load-bearing capacity of the beam, which in turn leads to higher strains in the concrete under the same load. The presented modelling approach based on the finite element method provides an effective way to predict the actual behaviour of reinforced concrete beams and forms a basis for further validation through experiments and comparison with theoretical calculations.

### 3. Scientific novelty and practical significance

The scientific novelty of the study lies in the preparation of a consistent and effective methodology for nonlinear FEM analysis of reinforced concrete span bridge structures, with the possibility of studying their stress-strain state in detail. The obtained stress-strain data will serve as a basis for further investigations of more complex effects on the bearing capacity of span structures, with the potential to take

into account different types and combinations of actions, as well as for further development of calculation methods for damaged bridge structures.

## Conclusions

In this study, a nonlinear finite element method (FEM) model of a reinforced concrete beam-and-slab bridge span was developed and calibrated using the geometry, reinforcement layout and material properties of a tested prototype. Five beam configurations with tensile reinforcement diameters ranging from 20 mm to 12 mm were also analysed under the same load level. The FEM simulations provided detailed distributions of stresses, strains and deflections for each configuration and demonstrated that decreasing the diameter of the tensile reinforcement leads to an increase in strains in both concrete and steel, with concrete strains rising by up to about 9% and reinforcement strains by up to about 40%, which reflects a reduction in flexural stiffness and safety margin. For the load level considered, the calculated strain values remained below the ultimate code limits, so all beams operated within the serviceability limit state and did not reach the ultimate limit state of bearing capacity. Overall, the results show that the finite element method offers a reliable tool for assessing the behaviour of reinforced concrete beam bridge structures with varying reinforcement layouts and can be used in further scientific research and in practical engineering applications related to the evaluation, optimisation and reconstruction of existing and new bridge spans.

## Acknowledgement

*This work was supported by the National Research Foundation of Ukraine (Grant No. 2023.05/0026).*

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