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APPROACHES TO CALCULATING REINFORCED CONCRETE SLABS STRENGTENED BY ADDING A CROSS-SECTION OF CONCRETE

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Abstract. The article presents a study of calculation and design methods for strengthening reinforced concrete floor slabs by installing an additional layer of cast-in-place concrete. The relevance of the topic is determined by the need to extend the service life of existing buildings in Ukraine under increased service loads, changes in the functional use of premises, and stricter reliability and safety requirements. A historical analysis of the development of shear-friction theory is carried out - from initial studies to modern fracture-mechanics models that form the normative basis for the design of interface joints in reinforced concrete members. A comparative analysis of analytical expressions for determining the shear capacity of the "old-new concrete" interface is performed in accordance with national (DBN, DSTU) and foreign codes (Eurocode 2, ACI 318, CSA A23), and approaches to accounting for adhesion, friction and mechanical interlock due to surface roughness and shear keys are summarised. Differences in the treatment of the components of shear resistance, which directly affect the amount of steel required for strengthening, the necessary thickness of the additional concrete layer, and the requirements for preparation of the contact surface, are identified. Particular attention is paid to the methodology of numerical modelling of the stress-strain state of strengthened slabs in specialised software packages such as LIRA-SAPR and others, including issues of selecting finite element types and modelling the interface joint. Recommendations are provided on the rational combination of analytical calculations and numerical modelling results in the design of strengthening solutions, and directions for further research aimed at refining design models and improving the efficiency of structural solutions are outlined. The obtained generalizations can be used to substantiate structural solutions for strengthening floor slabs and to improve the reliability of their calculations at various stages of design.

Keywords: strengthening of reinforced concrete slabs, concrete overlay, interface joint, shear forces.

Introduction. The construction industry in Ukraine and worldwide is currently largely focused on the reconstruction and rehabilitation of existing buildings and structures. A substantial proportion of RC structures commissioned in the second half of the twentieth century are now in a condition approaching the limit state with respect to physical deterioration criteria, or require adaptation to updated regulatory requirements and increased service loads [1-2]. Floor slabs, as the primary horizontal rigidity diaphragms and elements directly carrying imposed loads, are susceptible to defects associated with excessive deflections and crack formation. In addition to physical deterioration, there is often a need to strengthen floor systems when the functional use of spaces changes (e.g., conversion of office areas into storage or archival facilities, installation of heavy equipment on roofs, etc.) or when rectifying design and construction errors [3-4].

Among the wide range of methods for restoring load-bearing capacity-from the installation of additional beams [5-6] to external strengthening with carbon fibre strips [7-8] – the method of cross-sectional enlargement with concrete plays an important role [9-10]. This technique involves the construction of an additional layer of reinforced concrete on top of the existing slab, which makes it possible to increase the effective depth of the cross-section, enhance its flexural and shear stiffness, and, if required, restore the concrete cover to the reinforcement [11-14].

However, the design of strengthening by cross-sectional enlargement is associated with a number of complex engineering and scientific challenges. The key issue is ensuring reliable composite action between the "old" concrete and the "new" layer. If a reliable interface is not provided, the structure will behave as two independent slabs sliding relative to each other, which will lead to a significant reduction in load-bearing capacity and stiffness compared with a monolithic cross-section [15]. The mechanics of force transfer through the interface joint, which involves adhesion and friction, is complex and depends on many factors, including surface roughness, concrete strength class, the magnitude of normal stresses, shrinkage strains, and others [16].

Analysis of recent research and publications. The issue of ensuring composite action between concretes cast at different times remains a subject of active scientific investigation, while the fundamental concepts of the mechanisms governing force transfer across cracks and interface joints were established in the mid-twentieth century; the development of design methods for interface joints has been inextricably linked to the evolution of reinforced concrete theory, and in the first half of the twentieth century, calculation models were predominantly based on empirical rules that treated concrete as a homogeneous medium and did not account for the nature of crack opening.

A revolutionary milestone was achieved through studies conducted in the 1960s. Birkeland and Birkeland were the first to formulate the hypothesis of the "shear-friction theory" [17]. They proposed treating the failure or interface surface as a rough, serrated structure. According to their model, when one concrete part attempts to slide relative to another, the surface asperities “ride up” over each other, which results in a forced separation of the surfaces (Fig. 1).

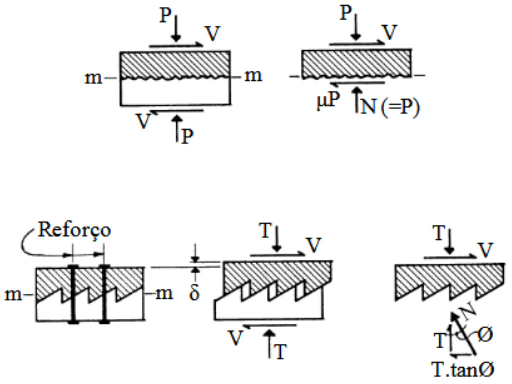

Fig. 1. Shear-friction theory model

If the interface joint is crossed by reinforcement, this separation induces tensile forces in the bars. In response, the reinforcement, acting in the elastic or plastic stage, generates a compressive force at the interface, which in turn mobilises frictional resistance. This mechanical model became the basis for design expressions adopted in most international codes, including ACI 318 (9).

In the late 1960s and the 1970s, Mast and Hofbeck [18] extended this theory by introducing the concepts of bond and the influence of externally applied normal forces. They demonstrated that, even in the absence of transverse reinforcement, the interface can resist substantial shear forces due to chemical adhesion and mechanical interlock of the aggregate, particularly for high-strength concrete.

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Purpose and objectives. The purpose of this article is to systematise approaches to the design of RC slabs strengthened by cross-sectional enlargement, taking into account the requirements of modern regulatory documents and the capabilities of advanced software packages.

Comparative analysis of codified approaches to the design of the interface joint. The design of strengthening of RC floor slabs is an important stage in engineering practice, as it determines the safety and durability of buildings and structures. This is also important from the standpoint of economic efficiency, since strengthening existing structures is often a more cost-effective solution than complete replacement or reconstruction.

The design of slabs strengthened by cross-sectional enlargement in accordance with previously applicable standards [20] was based on simplified procedures, in which primary attention was paid to the strength of concrete and reinforcement, as well as the stiffness of the structural system. The main emphasis was placed on considering the enlarged cross-section as part of a homogeneous structure, without a detailed allowance for potential slip between the new and old concrete. This implied that, under conditions of adequately ensured bond (roughened surface, mechanical anchors, etc.), the structure behaved as an integral unit. This made it possible to provide the required load-bearing capacity under standard conditions; however, it did not account for all possible time-dependent changes in material properties.

With the transition to the Ukrainian DBN, the requirements for the verification of strength and bond reliability between the old and new concrete have been specified in greater detail [21]. The approach is based on accounting for the composite action of the new and existing cross-sections; however, additional requirements for construction quality control have been introduced, including appropriate methods for connecting old and new structural elements. According to [22], criteria are provided that include the assessment of transverse shear forces, friction coefficients, the adhesive properties of the interface surfaces, and additional reinforcement at the interface. The design of such structures предусматриває verification of shear stresses at the interface surface, which shall satisfy the following conditions:

$$V_{Ed} \le V_{Rd},$$

where V_{Ed} is the design value of the shear forces, and V_{Rd} – is the shear resistance at the interface.

To account for the influence of surface roughness parameters and the stress state in the joint zone between the new and the existing concrete parts, coefficients are used that depend on the type of interface surface (smooth, rough, or indented). An important aspect is ensuring adequate reinforcement at the interface, which prevents relative displacement of the layers (Fig. 2). Such a methodology makes it possible to consider not only the physical properties of the materials but also the structural parameters that significantly affect the strength and deformability of strengthened RC slabs.

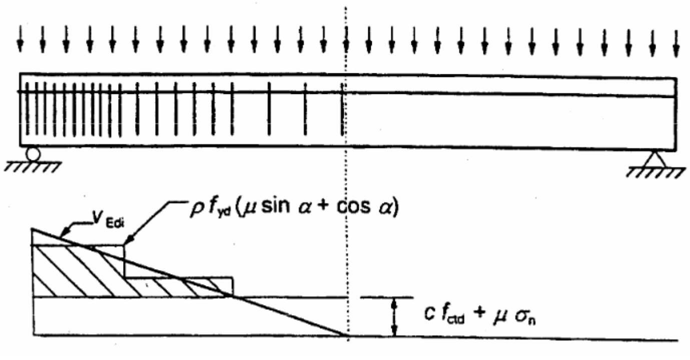

Fig. 2. Shear stress diagram illustrating the required interface reinforcement

Eurocode 2 [23] requires a thorough assessment of the bond between the old and the new concrete, which depends on surface roughness and mechanical anchorage. If the bond is poor or absent, separate design checks are stipulated for each layer, which significantly reduces the overall load-bearing capacity. The European provisions place considerable emphasis on long-term effects such as concrete creep and shrinkage. It is important to properly evaluate how these effects influence strain compatibility between the new and the old concrete in order to avoid undesirable stress redistributions. The use of reinforcement in the new concrete layer is also envisaged, and verification of its placement and compliance with the design parameters is required to ensure sufficient load-bearing capacity. In addition, composite materials may be applied for supplementary strengthening, which enables an increase in the strength and durability of the structure. A critical step is the correct determination of the shear resistance at the interface between the new and the old concrete.

Study [24] analyses how different international standards propose different approaches to assessing the strength of the joint between old and new concrete when strengthening RC slabs by cross-sectional enlargement. In particular, in Model Code 1990 the interface shear strength is calculated by considering cohesion and friction, which are determined using tabulated coefficients. The upper limit of shear strength is set at 25% of the concrete compressive strength, which serves to limit the forces that can be transferred across the joint. In Eurocode 2, the approach is similar; however, it additionally accounts for the influence of the inclination angle of the reinforcement crossing the joint and the normal stresses arising in the contact zone between the old and the new concrete. In this case, the maximum strength is limited to 50% of the concrete compressive strength. The Canadian standard CSA A23.3 introduces a coefficient λ that accounts for the possibility of cracking along the shear plane, which may occur due to relative movement between the old and the new concrete. The maximum joint strength in this case is also limited to 25% of the concrete compressive strength. ACI 318-11, unlike the European and Canadian approaches, focuses exclusively on the reinforcement crossing the layers, without detailed consideration of cohesion and friction. The shear strength in this standard is limited to the minimum value of 0.2fc or 5.52 MPa, depending on the condition of the old-concrete surface. Table 1 illustrates how different standards address the calculation of joint strength between the old and the new concrete during structural strengthening.

Table 1 – Strength of the interface joint between old and new concrete according to different standards

Design code	Year	Equation
Model Code 1990 [25]	1993	$\tau_R = c.\, f_{ctd} + \mu.\, (\sigma_n + \rho.\, f_y) \leq 0.25.\, f_{ctd}$
Eurocode 2 [24]	2004	$\tau_R = c.\, f_{ctd} + \mu.\, \sigma_n + \rho.\, f_y.\, (\mu.\, \sin\alpha + \cos\alpha) \leq 0.5.\, \nu.\, f_{cd}$
CSA A23.3-04 [26]	2004	$\tau_R = \lambda.\, \phi_c.\, (c + \mu.\, (\sigma_n + \rho.\, f_y.\, \sin\alpha)) + \phi_2.\, \rho.\, f_y.\, \cos\alpha \leq 0.25.\, \phi_c.\, f_c$
ACI 318-11 [27]	2011	$\tau_R = \rho.\, f_y.\, (\mu.\, \sin\alpha + \cos\alpha)$
Model Code 2010 [28]	2013	$\tau_R = c.\, f_c\, 1/3 + \mu.\, (\sigma_n + \rho.\, k.\, f_y) + \alpha.\, \rho.\, \sqrt{f_c.\, f_y} \leq \beta_c.\, \nu.\, f_{cd}$

Features of modelling in the LIRA-SAPR software package. Modelling of the stress-strain state of RC slabs is performed on the basis of the finite element method in the environment of the LIRA-SAPR software package or other software tools [29-30]. This enables the application of both simplified linear-elastic slab models and spatial materially nonlinear models that account for the actual structural behaviour, including concrete damage, cracking, and the real performance of the "old/new concrete" interface.

In [31], a spatial model based on solid finite elements of type SE-36 was used to analyse deflections of RC slabs strengthened by concrete overlay and supported along the contour (Fig. 3 and Fig. 4). The slab was discretised into a fine regular mesh in plan and into 12 layers through the thickness, which made it possible to assign different elastic moduli to individual layers and to vary slab stiffness. This approach is demonstrative for modelling strengthened slabs: the existing slab and the new concrete layer should be represented as separate layers within the solid model with individual material properties, while the reduction in stiffness in cracked zones should be introduced through adjustment of the elastic moduli.

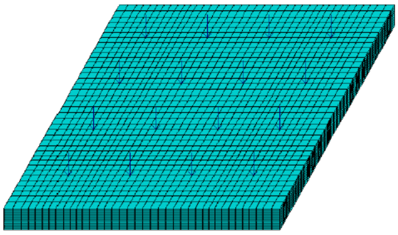

Fig. 3. Computational model of the slab in the LIRA-SAPR software package

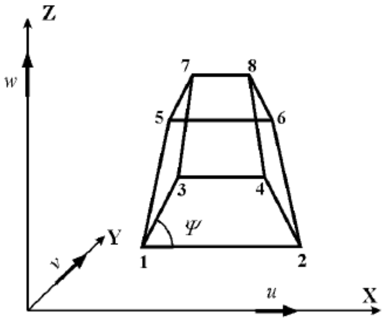

Fig. 4. Schematic representation of the SE-36 finite element

In [32], the slab was modelled using three-dimensional solid brick finite elements (analogous to FE-36 in LIRA-SAPR), which made it possible to capture the stress distribution through the entire thickness and the development of cracks. The concrete layers were defined as separate element sets with their own physical and mechanical properties (Fig. 5, Fig. 6). The "old-new concrete" interface was not modelled as perfectly rigid but rather through a system of contact nodes and nonlinear contact elements governed by a stress-slip (τ-s) relationship, which enabled partial opening and slip between the layers. The reinforcement was represented by embedded bar elements acting compositely with the solid concrete elements. This formulation made it possible to accurately reproduce the redistribution of shear stresses at the interface and a realistic deformation pattern, which is critical for analysing the behaviour of strengthened slabs.

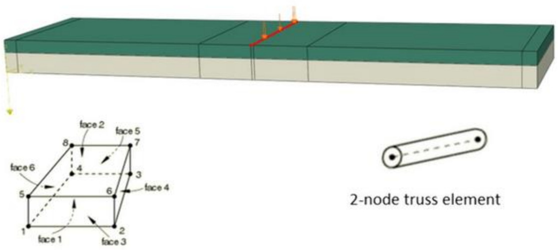

Fig. 5. Schematic of the test slab

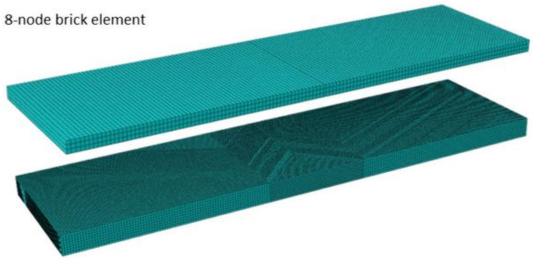

Fig. 6. Meshing of the slab and the strengthening layer

In [33], a comparison is presented of three approaches to the analysis of shell FE floor slabs available in LIRA-SAPR: linear analysis, materially nonlinear analysis, and analysis in the "engineering nonlinearity" mode. The linear model is used for the initial evaluation of displacements and for reinforcement design in accordance with code provisions. The materially nonlinear option is built on the same finite element scheme, but with allowance for the nonlinear constitutive behaviour of concrete and reinforcement (exponential or piecewise-linear σ-ε diagrams) and is implemented using a stepwise/stepwise-iterative procedure in the nonlinear processor. This makes it possible to analyse stiffness degradation of the slab with increasing load, as well as crack opening width and crack depth, which is fundamentally important when assessing the effectiveness of slab strengthening by cross-sectional enlargement.

In [34], several two-dimensional finite element models of reinforcement-concrete bond were developed in the LIRA-SAPR software package, based on introducing special bond bar elements FE-210 between plate elements representing concrete and reinforcement (Fig. 7, Fig. 8). The bond elements act in tension, compression, or shear, have their own nonlinear deformation law, and allow reproduction of τ-s relationships for the interface layer, as well as the distributions of shear stresses, displacements, and strains along the anchorage length. By analogy with these models, the "existing slab – new concrete layer" interface can be described by a system of discrete elements that simulate the action of shear keys, anchors, surface roughness, or an adhesive interface, which constitutes a promising direction for refined analyses of slabs strengthened by cross-sectional enlargement.

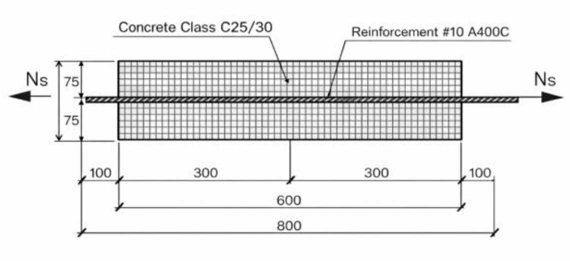

Fig. 7. Two-dimensional model of reinforcement–concrete bond

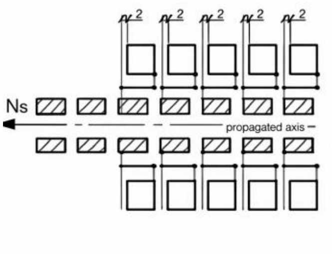

Fig. 8. FE discretisation of the model

Thus, several levels of modelling detail for floor slabs have been established in the LIRA-SAPR software package:

– simplified linear shell models with equivalent thickness and stiffness, used for preliminary selection of strengthening parameters;

– spatial models based on solid finite elements with layerwise-defined concrete properties for the existing slab and the new layer, in which nonlinearity is accounted for either by reducing the elastic moduli or by means of materially nonlinear analysis;

– models incorporating discrete bond elements, which make it possible to analyse the distribution of forces at the interface and the potential slip between layers.

Conclusions. The design of floor slabs strengthened by concrete overlay is based on the shear-friction theory. The DBN provisions and international codes allow the consideration of cohesion and other parameters. Numerical modelling in the LIRA-SAPR software package or other analysis tools using solid elements is important for the correct assessment of the stress-strain state. However, most existing recommendations propose limit-state-based design, treating the interface either as perfectly rigid or as fully separated. In contrast, the actual behaviour of a strengthened slab is often governed by an intermediate stage of partial slip, which affects both the strength and deformability of slabs. Ukrainian and European regulatory documents also differ in the empirical coefficients used for interface shear design, which complicates the adaptation of international experience. The procedures for accounting for shrinkage and creep between old and new concrete in domestic and foreign software packages are often reduced to simplified calculation approaches that do not represent the actual stress-strain state at the interface, which may lead to erroneous predictions of the overall load-bearing capacity of the strengthening system.

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ПІДХОДИ ДО РОЗРАХУНКУ ЗАЛІЗОБЕТОННИХ ПЛИТ, ПІДСИЛЕНИХ НАРОЩЕННЯМ ПОПЕРЕЧНОГО ПЕРЕРІЗУ БЕТОНОМ

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Анотація. У статті представлено дослідження методів розрахунку та проєктування підсилення залізобетонних плит перекриття шляхом улаштування додаткового шару монолітного бетону. Актуальність теми визначається необхідністю продовження ресурсу роботи наявних будівель України за умов підвищених експлуатаційних навантажень, змін корисного призначення приміщень і посилених вимог до надійності та безпеки. Проведено історичний аналіз розвитку теорії зсувного тертя – від початкових робіт до сучасних моделей механіки руйнування, що формують нормативну базу для розрахунку контактних швів залізобетонних елементів. Виконано порівняльний аналіз аналітичних залежностей для визначення міцності контактного шва «старий–новий бетон» відповідно до національних (ДБН, ДСТУ) та іноземних норм (Eurocode 2, ACI 318 ,CSA A23), узагальнено підходи до врахування адгезії, сил тертя та зчеплення за рахунок шорсткості поверхні і шпонок. Виявлено відмінності у врахуванні складових зусиль зсуву, які безпосередньо впливають на металоємність підсилення, необхідну товщину додаткового шару та вимоги до підготовки контактної поверхні. Окрему увагу приділено методології числового моделювання напружено-деформованого стану підсилених плит у спеціалізованих програмних комплексах таких як ПК Ліра Сапр та інші, зокрема питанням вибору, типів скінченних елементів та моделювання контактного шва. Наведено рекомендації щодо раціонального поєднання аналітичних розрахунків та результатів числового моделювання при проєктуванні підсилення, а також окреслено напрями подальших досліджень, спрямованих на уточнення розрахункових моделей і підвищення ефективності конструктивних рішень. Отримані узагальнення можуть бути використані для обґрунтування конструктивних рішень підсилення плит перекриття та підвищення достовірності їх розрахунку на різних етапах проєктування.

Ключові слова: підсилення залізобетонних плит, бетонне нарощення, контактний шов, зусилля зсуву.

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