Секция II

СТРОИТЕЛЬНЫЕ КОНСТРУКЦИИ ЗДАНИЙ И СООРУЖЕНИЙ, СОВРЕМЕННЫЕ МЕТОДЫ РАСЧЕТА И ПРОЕКТИРОВАНИЯ

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DESIGN METHOD FOR CAST IN-SITU FLOOR SLABD WITH EXTERNAL PROFILED STEEL DECK AS REINFORCEMENT

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This paper outlines research work carried out to establish a method of designing in situ cast floor slabs with external profiled steel sheeting reinforcements based on the use of "stress-strain" material diagrams. It details out experimental and analytical work carried out to investigating the effects of selected bonding devices on the concrete/profiled steel sheeting slip resistance, in which the effects of bonding embossment's depth and the concrete/profiled steel sheeting bonding length are considered. A model is developed to simulate load-deformation characteristics of profiled steel sheeting reinforced in in-situ-cast concrete floor slabs. Comparisons are presented between design solutions obtained by applying the worked out designing method and experimental results.

Keywords: *design methods, in-situ-cast, profiled steel sheeting, reinforcement "stress-strain" material diagrams.*

МЕТОД РАСЧЕТА МОНОЛИТНОЙ ПЛИТЫ ПЕРЕКРЫТИЯ С НАРУЖНЫМ ПРОФИЛИРОВАННЫМ СТАЛЬНЫМ НАСТИЛОМ В КАЧЕСТВЕ АРМИРОВАНИЯ

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В статье изложены научно-исследовательские работы, проведенные с целью создания методики проектирования монолитных плит перекрытия с наружным профилированным армированием из стальных листов на основе использования диаграмм материалов «напряжение-деформация». Подробно описаны экспериментальные и аналитические работы, проводимые по изучению влияния выбранных склеивающих устройств на сопротивление скольжению бетонных/профнастилных листов, в которых учитывается влияние глубины склеивания тиснения и длины склеивания бетона/профилированного стального листа. Разработана модель моделирования нагрузочно-деформационных характеристик профилирован-

ного стального листа, армирующего монолитные железобетонные плиты перекрытия. Приведены сравнения между проектными решениями, полученными с применением разработанной методики проектирования и экспериментальными результатами.

Keywords: *методы проектирования, монолитный бетон, стальной профилированный лист, диаграмма материалов «напряжение-деформация».*

Introduction. Over the past years, special attention has been paid to the question concerning industrial technical re-equipment, its rehabilitation and reconstruction. During exploitation, under the action of aggressive environmental conditions, high-temperature heating during fire hazards, dynamic loads, defects, and damages which essentially lower bearing capacity of structural elements are generated. As a result, there arises a need to rehabilitate, strengthen, and repair by replacing the damaged elements completely or selectively [16].

The replacement of reinforced floor slabs is the most manpower-consuming, complex and difficult work. The cost of these works makes up to about 25 % of the total costs attributed to reconstruction. The use of already made (precast) reinforced concrete elements as replacement is complicated due to constrained conditions of installation and the impossibility of using high efficiency mounting mechanisms.

One of the effective ways of solving this problem is the application of profiled steel sheeting reinforced *in-situ-cast* concrete slabs. In this flooring system, profiled steel sheeting acts as permanent formwork during concreting (construction) and tensile reinforcement during service (exploitation). This class of slabs can also be successfully used during the erection of floor slabs of new structures with complex configuration in plan as well as in slabs where plenty of technological openings are required [16].

Background. The calculation of bearing capacity of profiled steel sheeting reinforced *in-sit-cast* concrete slabs, is based on the classical theory of reinforced concrete elements in which *stress-strain* state of sections is analyzed only at ultimate state. This method does not consider the shear bond failure mode and the weakening of the profiled sheet's walls by the embossments, which are normally predominant and characteristic for the given class of slabs and are approximated empirically in the classical theory-based method. At present, the most perspective way of improving and perfecting methods of designing reinforced concrete elements is by the application of material stress-strain analytical relationships. This allows maximization in the utilization of material strength properties in structural design, assess the *stress-strain* state at all loading stages, and in some cases, this results in a reasonable economy of building materials [1-6, 13].

In the building codes of many countries, mainly two methods of calculation are applied – the Limit States Method, which is predominant in the western countries, and the Ultimate State Method which is currently applied in the Countries of Independent States (the former USSR). In these methods, the *in-situ-cast* concrete slab's normal section is considered as a transformed reinforced concrete cross-section without taking into consideration tensioned concrete in the section and in between cracks.

Strength calculation of sections normal to the element's longitudinal axis in the service stage, applying the Ultimate State Method is based on the commonly adopted for reinforced concrete relationships (dependencies). The profiled steel sheeting's calculated strength is multiplied by a coefficient, which is assumed to consider non-uniform normal strain (deformation) distribution. Specialist's opinions differ on the numerical value to be considered for this coefficient [7; 9; 11; 14].

Normal section strength calculations are carried out without considering the following: *the compliance (end-slip of concrete relative to profiled steel sheeting) of the span contact interface of profiled steel sheeting and concrete, the presence of "embossments" on the reinforcing steel sheeting's walls which reduce their sectional tensile strength.*

The concrete/profiled steel sheeting slip is considered empirically only during slab deflection (flexural) calculations when applying the current classical theory-based method.

The widely spread computerization of designing methods of building elements, the intention to fully formulate mathematically the *stress-strain* state of elements under the action of loads, the desire for design methods of reinforced concrete elements to be maximally realistic (to depict more closely the element's actual stress-strain state), revealed a perspective acknowledgement in the application design methods based on material “stress-strain” deformation models of structural elements. Research on the normal section stress-strain state, applying the material deformation models for *in-situ-cast* reinforced concrete floor slabs with external reinforcement, has not been carried out. As a result, this new approach needs to be developed and tested for its applicability in *in-situ-cast* concrete floor slabs reinforced by external profiled steel sheeting.

The essential integral action between profiled steel sheeting and concrete depends on the strength and compliance of interlocking devices, capable of resisting horizontal shear and preventing vertical separation of the steel/concrete interface. Integral work of profiled steel sheeting with concrete can be achieved in various ways [5; 6; 15; 16]. The most satisfactory methods of achieving this action are *by punching ‘embossments’ onto the surface of profiled steel sheeting walls and on-site welding of stud shear connectors*.

The first method is preferable in that, the punching of ‘embossments’ can be carried out during the profiled steel sheeting’s production (moulding), which excludes the carrying out of labour-consuming works of punching or welding devices on to the reinforcing profiled steel sheeting under construction site conditions. Besides, during reconstruction, on-site welding of stud shear connectors can be complicated by the absence of mortgage devices or their unsatisfactory physical state (corrosion). Beforehand mounted stud shear connectors can be a danger to workers carrying out the construction work.

The inequalities of *in-situ-cast* concrete slabs with external reinforcements lies in that: cracks in concrete are closed from below by the profiled steel sheeting and aggressive agents (effects of surrounding aggressive environment) do not penetrate concrete. This fact necessitates the effective use of additional high strength reinforcing bars in *in-situ-cast* concrete slabs with external profiled steel sheeting [16].

The **aim** of this work is to develop a material “stress-strain” deformation model-based design method of *in-situ-cast* concrete floor slabs with external profiled steel sheeting as reinforcement.

In accordance with the aim of the work, the following tasks were carried out:

– Development of methods to consider concrete-profiled steel sheeting slip of the contact interface and the presence of embossments on the profiled steel sheeting’s walls in the in-situ-cast concrete floor.

– Researching on embossments and end-anchors which provide optimal integral action between concrete and the profiled steel sheeting reinforcements of the in-situ-cast concrete floor slabs.

– Obtaining experimental confirmation of hypotheses adopted in the developed method of design of the in-situ-cast concrete floor slabs.

– Obtaining experimental (data) acknowledging (confirming) the additional advantages of using additional unstressed high strength reinforcing bars in the in-situ-cast concrete floor slabs with external reinforcement.

Experimental Programme. The experimental part of the research work was carried out in two stages.

First Stage. With the aim of obtaining *"load – slip deformation"* relationships and asses the influence of the types of anchoring devices (embossments and end-anchors), sample-fragments were tested for slippage. The experimental research method was adopted since, the currently known design methods do not allow, theoretically, to determine slip relationships of profiled steel sheeting relative to concrete of an element section having variable shapes, sizes and locations of anchoring embossments punched on the profile steel sheeting's walls using cold punching methods.

Sample - fragments (specimen) for this part of research were cut out pieces of profiled steel sheeting, filled with concrete. 51 sample – fragments were tested.

The experimental research work was carried out on the following types of anchoring devices: embossments; in the form of a "butterfly", rectangular and inclined (embossments with an inclination angle to the profiled steel sheeting's longitudinal axis of 30^o, 45^o, 75^o, 90^o), end-anchors, iron bars, and profiled steel sheeting cut-flanges. The embossment dimensions were selected in such a way that the total area of their surface in contact with concrete was the same for all samples. Besides, the following parameters were varied: embossment depth (4 mm, 6 mm, and 8 mm); bonding length (200 mm, 400 mm, 600 mm, and 800 mm).

Testing of sample - fragments was carried out by the slippage of concrete block relative to the firmly fixed to the testing stand profiled steel sheeting. The sample - fragments were loaded in steps of 0,05 - 0,1 tones using a 5-tone hydraulic jack, placed horizontally against one of the samples – fragment's ends. The concrete/profiled steel sheeting slip was measured using 0.001-mm dial gauge indicators fixed at the other free sample – fragment end. The results of the first stage were used in slab specimen for the second state.

With the aim of obtaining profiled steel sheeting *stress-strain* (deformation) diagrams, 500 mm × 500 mm × 60 mm flat steel sheets cut from the profiled steel sheeting's walls were tested for axial tension (Figure 2). To obtain strain-stress diagrams of profiled steel sheeting with embossments, plain steel sheeting pieces without embossments were also axial tensile tested (Figure 3).

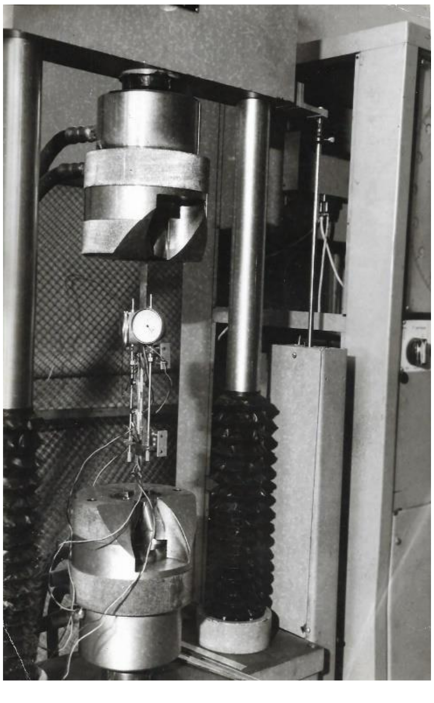


Figure 1. – Tensile testing of steel profiled strip prototypes

Second Stage. On this stage of the experimental part of the research work, two series of one span floor slabs were tested for flexure. Varied parameters were, length of slab samples (3000, 6000 mm), concrete/profiled steel sheeting anchoring methods (embossments, end-anchors, and end-anchors); the presents or absences of additional reinforcing bars.

The sample-fragments and floor slabs were reinforced using a 0.8 mm thick profiled steel sheeting produced by the Malodechno Light Metal-Construction Plant located in the town of Malodechno in the republic of Belarus. 12 mm diameter $A_T - IVC$ reinforcing bars were used as additional reinforcements (a bar in each goffer). The slabs were concreted using heavy concrete with an average cubical strength of 23…24 MPa. Height of concrete above the profiled steel sheeting was varied within the 125…130 mm range.

The first of the two series' floor slab specimen $of\ length = 300\ mm$ were tested using a one span testing scheme, loaded with two concentrated point loads, positioned symmetrically from the center (see Figure 4). Second series floor slab specimen of $length = 6000\ mm$ were also tested using a one span testing scheme, loaded with four concentrated point loads, positioned symmetrically from the center.

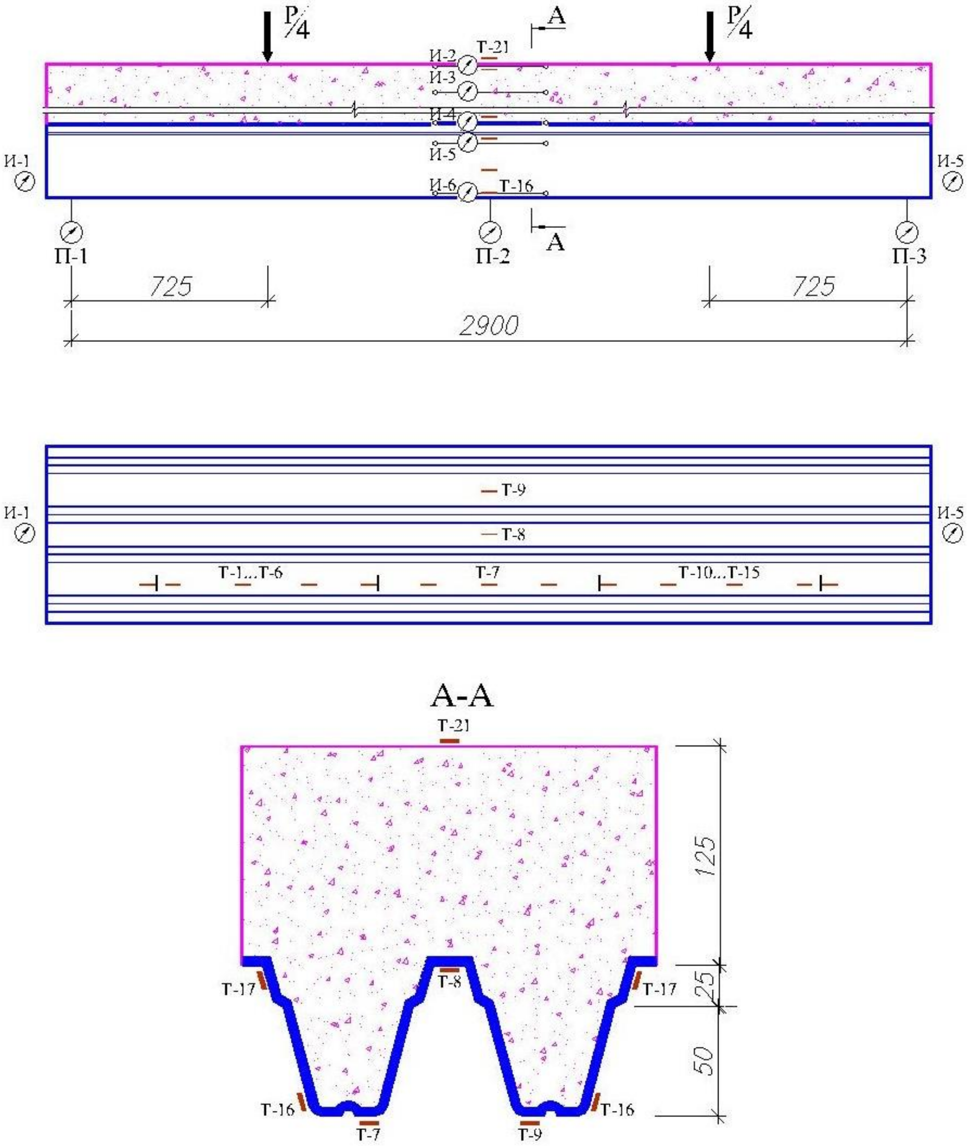


Figure 2. - Scheme of installation of measurement devices
when testing experimental slabs: u – watch-type indicator; n - deflector meter

During testing, mid-span deflections (flexure), concrete/profiled steel sheeting slippage, concrete and profiled steel sheeting relative strain (deformation) were recorded.

Experimental Results

First Experimental Stage Results. “Load – slip deformation” relationships which are approximated by a two segmented linear diagram were obtained as shown in Figure 5. The first segment represents the elastic work stage of the anchoring devices and the second segment represent elastic-plastic stage. The segments of the diagrams are determined by the following equation:

$$T = b + a\Delta, \tag{1}$$

where T – shear load;

Δ – slip deformation (shear) of concrete block relative to profiled steel sheeting. Coefficients a and b were determined during test results (data) analysis.

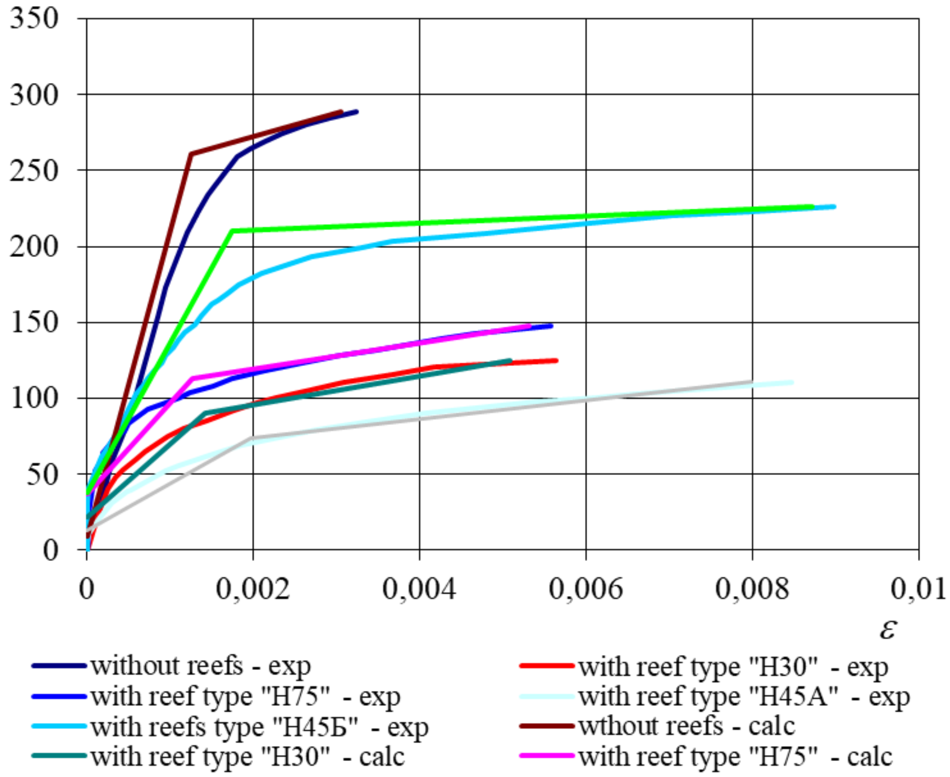


Figure 3. – Material deformation diagrams for profiled steel prototypes

Experimentally, it was established that embossments with a 45° inclination angle to the profiled steel sheeting’s longitudinal axis and having a $h/t = 0.2$ ($h -$ embossment depth, $t -$ embossment pitch distribution) relationship, as well as end-anchors in the form of cut-flanges, provide *satisfactory* shearing resistance to the concrete/profiled steel contact interface.

Research on sample - fragments with embossments having varied depth h_{rif}, showed an increase in failure shear loads with an increase in embossment depth which is recommended to be calculated applying the following equation:

$$T = -30.6 + 229.2h_{rif}. \tag{2}$$

This equation is valid within the embossment depth limits $4\ mm \le h_{rif} \le 8\ mm$.

The effects of profiled steel sheeting bonding length on the concrete/profiled steel sheeting slip resistance have been established to be computed applying the equation:

$$T = 1350 + 2.1L. \tag{3}$$

This equation is valid within the bond length limit of $200\ mm \le L \le 800\ mm$. Besides, it has been established that, with an increase in bond length, failure shear loads increases whilst the bond stress τ_{cs} decreases.

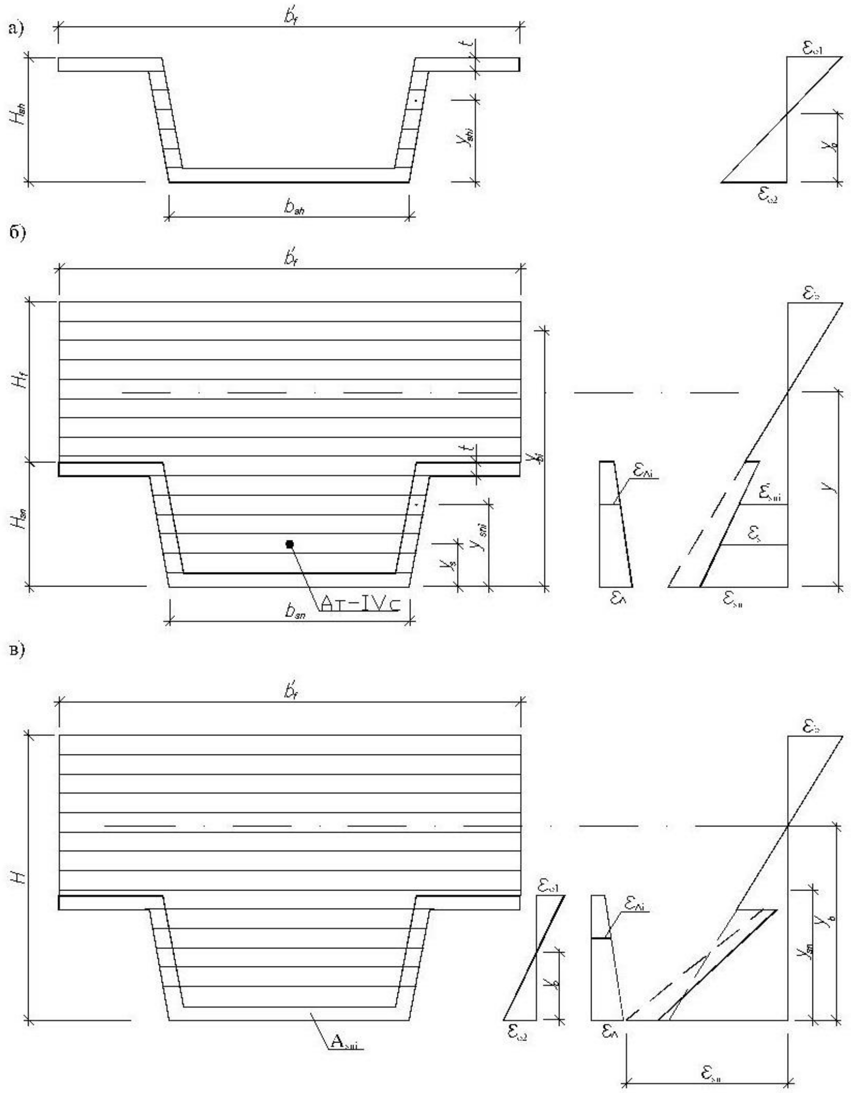
Diagrams of relative slip deformations (strain) to be used in the designing deformation model were obtained from the determined "$T = \Delta$" experimental relationships.

$$\varepsilon_{\Delta i} = \frac{2\Delta_i}{L}, \tag{4}$$

where L – span length (distance between supports). Based on the slip test results of the sample - fragments, relative deformation (strain) of the i-elemental layer $\varepsilon_{\bar{sn},i}$ under constant bond stress can be formulated as follows:

$$\varepsilon_{\bar{sn},i} = \varepsilon_{sn,i} + \varepsilon_{\Delta i}. \tag{5}$$

Theoretical Designing Method



а) – during the concreting stage; б) – during the operation stage without considering the initial deformation of the deck; в) – during the operation stage considering the initial deformation of the deck

Figure 4. – Design diagram of floor slabs reinforced with profiled steel deck (reefs conditionally not shown)

This part outlines the establishment (processing) of method of assessing the "stress-strain" state and the bearing capacity (designing) of normal cross section of *in-situ-cast* profiled steel sheeting reinforced concrete floor slabs, based on the use of full (whole) material deformation diagrams. In view of the adopted deformation model, the reinforced concrete element normal section was considered as a set of layers within the limits of which deformations are taken to be evenly and equally distributed as shown in figure 5 above [12; 8; 15; 16].

The reinforced concrete element's "stress-strain" state is described by the equilibrium equations and average relative deformation (strain) in accordance with the transverse plane section hypothesis as well as by the relationship between relative deformations (strains) and stresses of elemental layers.

$$\begin{cases} \sum_{i=1}^{n} E_{mi}\varepsilon_{mi}A_{mi}\left(y_o - y_{mi}\right) - M = 0 \\ \sum_{i=1}^{n} E_{mi}\varepsilon_{mi}A_{mi} = 0 \\ \varepsilon_{mi} = \frac{1}{r}\left[y_o - y_{mi}\right] \\ E_{mi} = f\left(\varepsilon_{mi}\right) \end{cases} \tag{6}$$

where E_{mi} – secant deformation modulus of concrete and reinforcements of $i - elemental\ layer$;

ε_{mi} – relative strains $of\ \ i - \ elemental\ layer\ (area)$;

y_0 – distance from the bottom of the reinforced element's section to its flexural axis;

y_{mi} – distance from the adopted element's neutral axis to the $i - elemental$ layer's center of gravity;

A_{mi} – cross-sectional area of an elemental layer;

n – number of elemental layers and reinforcements in a section;

M – flexural moment.

The reinforced floor slabs' failure criterion was adopted as either the crushing of concrete in the compressed zone or the rupture of reinforcements in the tensioned zone. When consecutively loading, maximum loads at which equilibrium conditions are satisfied correspond to the bearing (carrying) capacity of the reinforced concrete element.

Methods of accounting compliance (slip) of the interface contact seam of concrete and profiled steel sheeting and slab bearing capacity effects of embossments stamped on the profiled steel sheeting's walls were experimentally established in the first experimental stage of the research work.

When processing steel sheet's tensile testing results, "stress - strain" material diagrams for profiled steel sheeting with punched embossments were obtained. In the calculations, segment - linear functions, approximating real diagrams acquired during axial tensile testing results were used as initial input stress - strain relationships for profiled steel sheeting with embossments on their walls.

Bearing capacity calculation algorithm of the reinforced concrete slab's normal sections is accomplished (realised) using a step - by - step consecutive loading method. At each iterated calculation stage, relative strains (deformations) at the gravity center level of each $i - elemental\ layer$ are defined. The stage iteration is considered complete if the required (demanded) calculation accuracy conditions are satisfied.

The worked-out *stress* - *strain* based design method is realised applying a computer program "SLABS" written by the author(s).

Second Stage Experimental Results

The collapse (slab failure) of the first group experimental specimen occurred at the normal section near one of the concentrated point loads (Figure 3). The results analysis showed that the length distributed anchoring devices (embossments), initially concentrate "steel - concrete" tangential bond stress on themselves. At this stage end-anchors partially participate in the concrete-steel bonding. With the increase in external loads, concrete/profiled steel sheeting contact seam shearing (slippage) arises, and the end-anchors (cut-flanges) more intensively participate in the concrete-steel sheeting bonding. At the moment of slab failure, the bond stress is redistributed from the embossments to the end-anchors.

The experimental test showed that, second group specimen floor slabs also including the ones with combined reinforcements (profiled steel sheeting and additional reinforcing bars) had a normal section failure occurring in the zones under the action of maximum flexural moment with crushing of concrete in the compressed zones The strains in the reinforcements (profiled steel sheeting and additional high strength bars) were more than strains corresponding to characteristic yield strength of reinforcements. Slip of profiled steel sheeting relative to concrete, was insignificant (not recorded), although in some places in the mid-span regions of the floor slabs, peeling off from the profiled steel sheeting from concrete was observed. The research has confirmed the effectiveness of using additional unprestressed high strength reinforcing bars in situ cast reinforced concrete floor slabs with external profiled steel sheeting reinforcements.

Bearing capacity calculations of second group specimen floor slabs were carried out without taking into consideration the shearing (slip) of concrete/profiled steel sheeting interface seam. Results analysis showed that theoretical (calculated) failure flexure moments, determined using the proposed design (calculation) method, have satisfactory convergence with experimental failure flexure moments (maximum moment deviations does not exceed 3.4%).

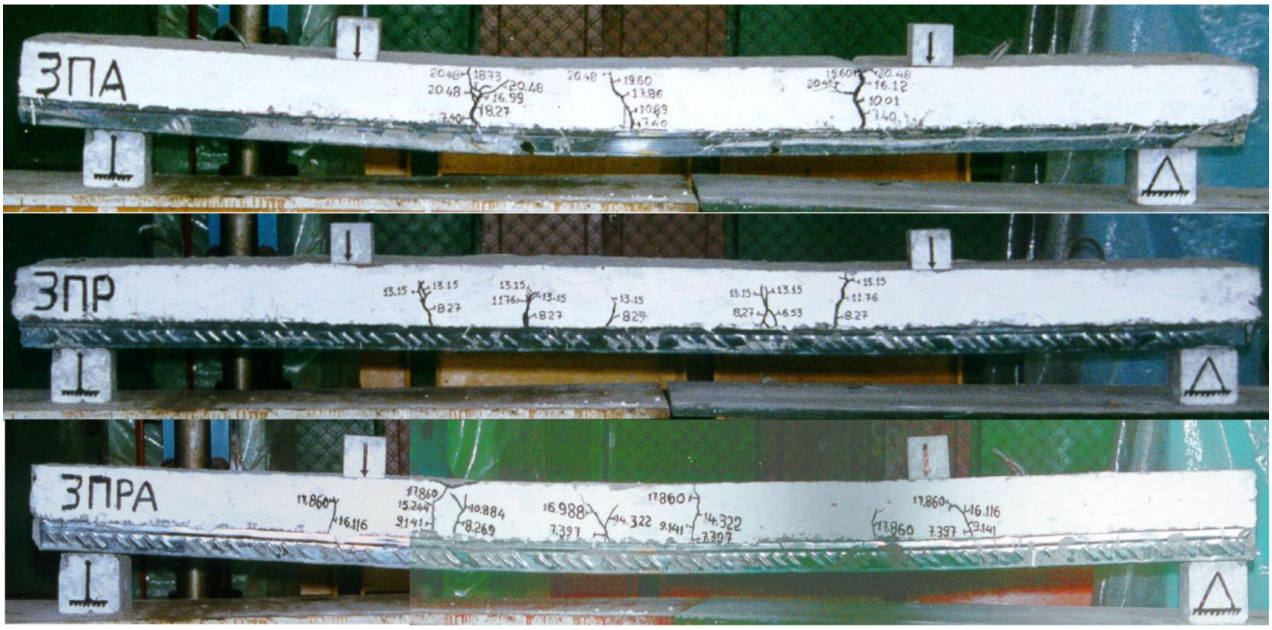


Figure 5. – In-situ-cast floor flab specimen externally reinforced by profiled steel sheeting after testing

Experimental research results confirmed the appropriateness of main assumptions adopted for the normal section calculation (designing) models of *in-situ-cast* floor slabs with external profiled steel sheeting as reinforcements, and the practical advantages (reliability) of the worked-out method over the currently used methods based on the classical theory of reinforced concrete elements. Distribution of relative strains along the height of normal sections obeyed the adopted normal transverse plane section hypothesis (Figure 3).

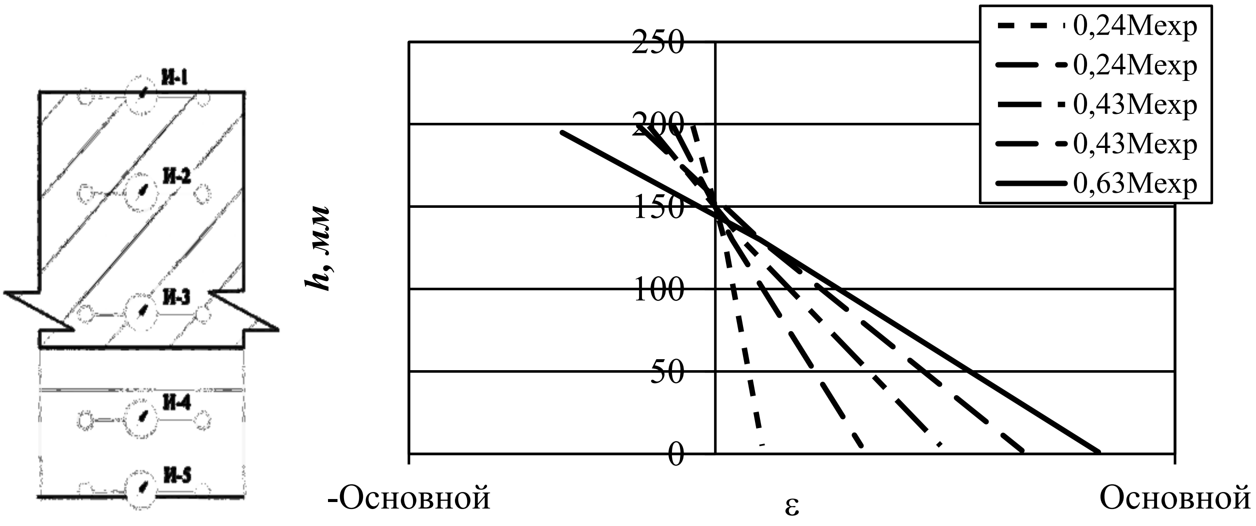


Figure 6. – Relative strain distribution along the height of the normal section at different loading stages

Deflection analysis of first group *in-situ-cast* floor slabs has showed much more effects of compliance of concrete/profiled steel sheeting contact interface seam on the deflection of in-situ-cast reinforced concrete slabs with profiled steel sheeting reinforcements.

Experimental mid-span deflection of specimen slabs was carried out using initial parameter (support conditions) equations of which in conjunction with the adopted deformation models take into consideration the rigidity of the slab’s sections. For consideration of span rigidity changes in the service period, the slab’s span is divided into segments. Conditionally, it is assumed that the slab’s rigidity changes in step-like format from the supports. In the calculations, an equivalent slab with constant rigidity replaces the actual slab. In that way, in view of the adopted designing (calculation) model, the compliance of the concrete/profiled steel sheeting interface contact seam is taken into consideration. A satisfactory convergence of calculated and experimental deflections of slabs under the action of service loads has been observed.

Conclusions. We can make the following conclusions.

1. Methods of computing shearing (slip) of contact interface seam of concrete and profiled steel sheeting, and structural element bearing capacity effects of embossments (stamped on the profiled steel sheeting's walls) in the form of transformed profiled steel *stress – strain* material diagrams were established.

2. A normal section bearing capacity and slab deflection calculation (designing) method based on the use of full material deformation diagrams has been established. This method allows for the determination of *stress – strain* state parameters of the *in-situ-cast* floor slabs at any loading stage and the shearing (end-slip of concrete relative to profiled steel sheeting) of the span contact interface seam of profiled steel sheeting and concrete.

The obtained result in this work clearly demonstrates the applicability of the proposed method of designing reinforced concrete elements based on the use of *“stress – strain”* material diagrams to *in-situ-cast* floor slabs with profiled steel sheeting as external reinforcements.

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