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MATERIAL STRESS-STRAIN DIAGRAM BASED DESIGN METHOD FOR CAST IN-SITU FLOOR SLABS WITH EXTERNAL PROFILED STEEL SHEETINGS AS REINFORCEMENTS

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This paper outlines research work carried out to establish a method of designing in situ cast floor slabs with profiled steel sheetings 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 sheetings 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.

Introduction. Over these past years, special attention is being 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 arise a need to completely or selectively replace damaged elements.

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.

The calculation of bearing capacity of profiled steel sheeting reinforced *in situ 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 take into account 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, asses the *stress-strain* state at all loading stages, arfd in some cases this results in a reasonable economy of building materials.

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 sheetings's calculated strength is multiplied by a coefficient, which is assumed to take into account non-uniform normal strain (deformation) distribution. Specialists's opinions differ on the numerical value to be considered for this coefficient.

Normal section strength calculations are carried out without considering the following:

- *the compliance (end-slip of concrete relative to profiled steel sheetings) of the span interface contact seam of profiled steel sheetings and concrete;*

- *the presence of «embossments» on the reinforcing steel sheetings 's walls which reduce their sectional tensile strength.*

The concrete/profiled steel sheetings 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, have 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 sheetings.

The essential integral action between profiled steel sheetings 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 by various ways. The most satisfactory methods of achieving this action are *by rolling «embossments» onto the surface of profiled steel sheeting and on-site welding of stud shear connectors.*

The first method is preferable in that, the rolling of «embossments» can be carried out during the profiled steel sheeting's production (moulding), which excludes the carrying out of labour-consuming works of rolling 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 uniqualities 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 (surroundings) do not penetrate into concrete. This fact necessitates the effective use of additional high strength reinforcing bars in *in situ cast* concrete slabs with external profiled steel sheeting.

The **aim** of the 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 work, the following tasks were carried out:

- *development of methods to take into account concrete-profiled steel sheeting slip of the contact seam 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.

On the ***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 due to the fact that, the currently known design methods do not allow, theoretically, to determine slip relationships of profiled steel sheetings relative to concrete of an element section having variable shapes, sizes and locations of anchoring embossments punched on the profile steel sheetings's walls using the cold punching methods.

Sample - fragments (specimen) for this part of research were cut out pieces of profiled steel sheetings, 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 - 30, 45, 75, 90°): 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, 6 and 8 mm); bonding length (200, 400, 600 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 pump (jack) placed horizontally against one of the sample - 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.

On the *Second 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 sheetings anchoring methods (embossments, end-anchors, embossments and end-anchors); the presents or absents of additional reinforcing bars.

The sample-fragments and floor slabs were reinforced using a 0,8 mm thick profiled steel sheetings produced by the Malodechno Light Metal-Construction Plant located in the town of Malodechno in the republic of Belarus. 12 mm diameter *Aj. - JVC* reinforcing bars were used as additional reinforcements (a bar in each and every goffer). The slabs were concreted using heavy concrete with an average cubical strength of 23...24 MPa. Height of concrete above the profiled steel sheetings was varied within the 125... 130 mm range.

The first of the two series' floor slab specimen (/ = 3000 mm) were tested using a one span testing scheme, loaded with two concentrated point loads, positioned symmetrically from the center. Second series floor slab specimen (/ = 6000 mm) were also tested using a one span testing scheme, loaded with four concentrated point loads, positioned symmetrically from the center.

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

With the aim of obtaining profiled steel sheeting *stress - strain* (deformation) diagrams, 500x60 mm flat steel sheets (cut from the profiled steel sheeting's walls) were tested for axial tension. To obtain diagrams of profiled steel sheetings with embossments, steel sheeting pieces with embossments were also axial tensile tested.

First experimental stage results. «Load - slip deformation» relationships which are approximated by a two segmented linear diagram were acquired. The first segment represent the elastic work stage of the anchoring devices and the second segment represent elastic-plastic stage. The segments of the diagrams are represented 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 sheetings. Coefficients a and b were determined during test results (data) analysis.

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 step distribution) relationship, as well as end-anchors in the form of cut-flanges provide *appropriate* shearing resistance to the concrete/profiled steel contact seam.

Research on sample – fragments with embossments having varied depth h_{rif}, showed an increace in failure shear loads with an increace 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 $4 \text{ мм} \le h_{rif} \le 8 \text{ мм}$.

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

$$T = 1350 + 2{,}3L. \tag{3}$$

This equation is valid within the bond length limit $200 \text{ mm} \le L \le 800 \text{ mm}$. Besides, it has been established that, with an increace 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 $\varepsilon^{-}_{sn,i}$ under constant bond stress can be formulated as follows

$$\varepsilon^{-}_{sn,i} = \varepsilon_{sn,i} + \varepsilon_{\Delta i}. \tag{5}$$

Theoretical Designing Method. This part outlines the establishment (processing) of method of assessing the «tress - strain» state and the bearing capacity (designing) of normal section of *in situ cast* profiled steel sheetings 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 (Fig. 1).

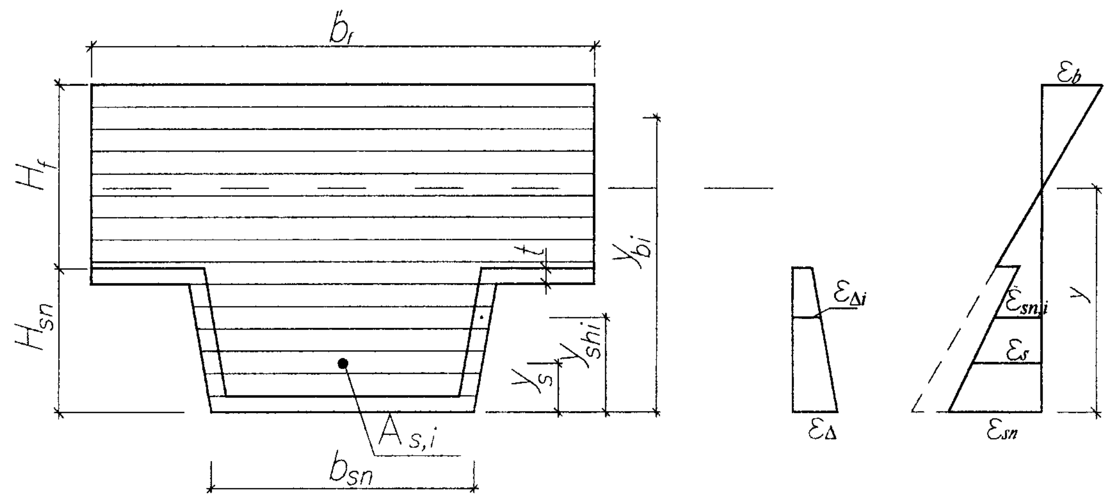

Fig. 1. Slab normal cross section and strain distribution on the section's height

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.

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

where E_{mi} – secant deformation modulus of concrete and reinforcements of *i*-elemental layer; ε_{mi} – relative strains of *i* – elemental y_o – 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 centre 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's 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.

When processing steel sheet's tensile testing results, «stress - strain» material diagrams for profiled steel sheetings with stamped 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 sheetings 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 centre level of each /'-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 (Fig. 2). 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 increace in external loads, concrete/profiled steel sheetings contact seam shearing (slippage) arises and the end-anchors (cut-flanges) more intensively participate in the concrete-steel sheetings 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 including also the ones with combined reinforcements (profiled steel sheetings and additional reinforcing bars) had a normal section failure occurring in the zones under the action of maximum flexural moment as a result of concrete crushing in the compressed zones (Fig. 2). The strains in the reinforcements (profiled steel sheetings and additional high strength bars) were more than strains corresponding to characteristic yield strength of reinforcements. Slip of profiled steel sheetings relative to concrete, was not recorded, although in some places in the mid-span regions of the floor slabs, peeling off of profiled steel sheetings 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 sheetings reinforcements.*

Bearing capacity calculations of second group specimen floor slabs were carried out without taking into consideration the compliance (slip) of concrete/profiled steel sheetings 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 %).

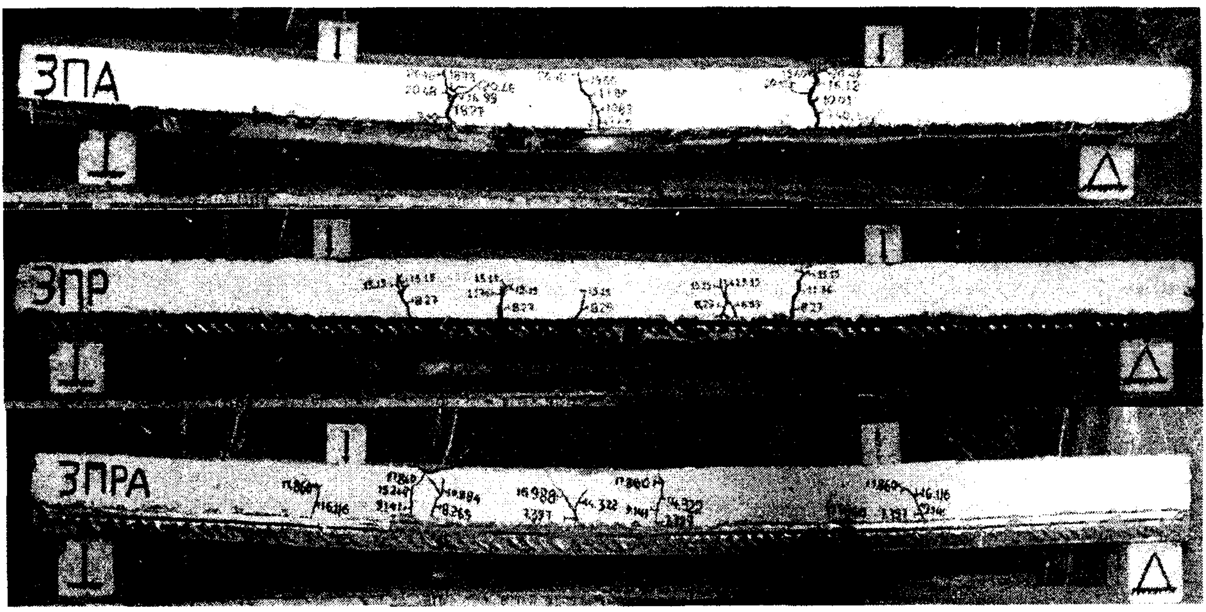

Fig. 2. *In situ cast* floor flab specimen externally reinforced by profiled steel sheetings after testing

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 sheetings 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 (Fig. 3).

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

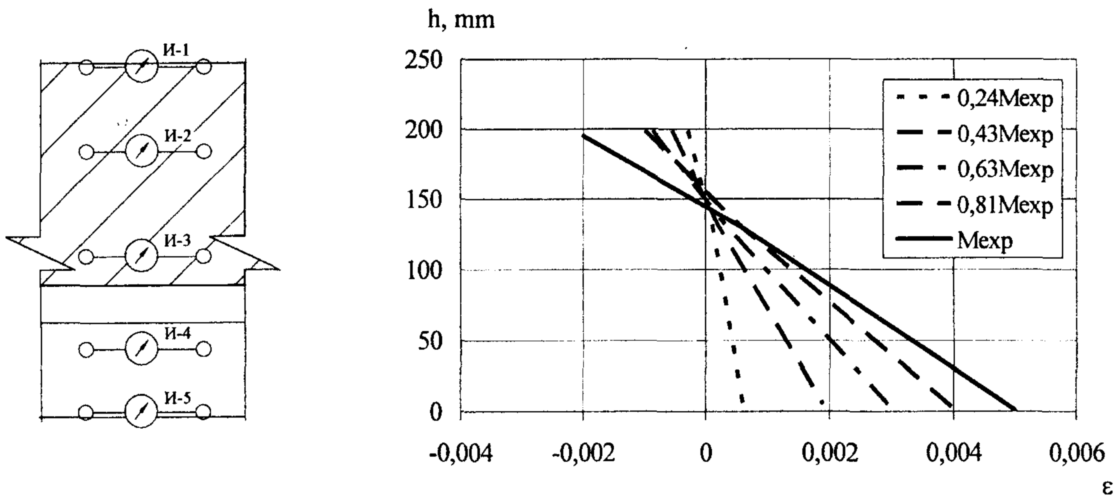

Fig. 3. Relative strain distribution along the height of the normal section at different loading stages

Conclusions

1. 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 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 sheetings) of the span contact interface seam of profiled steel sheetings and concrete. The research results have confirmed the effectiveness of using additional unstressed high strength reinforcing bars *in situ cast* reinforced concrete floor slabs with external profiled steel sheetings reinforcements.

2. Methods of computing shearing (slip) of contact interface seam of concrete and profiled steel sheetings, 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.

3. Experimentally, the effects of, embossment inclination angle, embossment depth and embossment quantity on the concrete/profiled steel sheetings shearing have been established. It was established that embossments with a 45° inclination angle to the profiled steel sheeting’s longitudinal axis and a h/t - 0,2 (h - embossment depth, t - embossment step distribution) relationship, as well as end-anchors in the form of cut-flanges provide appropriate shear resistance to the concrete/profiled steel contact seam.

4. The research results have confirmed the effectiveness of using additional unstressed high strength reinforcing bars *in situ cast* reinforced concrete floor slabs with external profiled steel sheetings reinforcements.

The obtained results 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 sheetings as external reinforcements.

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