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Calculation of steel-reinforced concrete structures made of cold-formed steel profiles under biaxial loading

Abstract. The aim of the work is to establish theoretical dependences for determining stresses at the extreme points of the cross-section of steel-reinforced concrete rod structures made of cold-formed steel profiles under biaxial bending loading. The steel part of the cross-section of the rod under consideration is a U-shaped profile, which is filled with concrete. At the first stage of manufacturing a prestressed rod, an initial bending of the steel part of the beams opposite to the operational one is created using mechanical jacks. During concreting of the U-shaped cavity and for the period of setting of the concrete to the design strength, the jacks under the steel beams remain. At the live load (third stage), the combined steel-concrete cross-section works together. In the concrete part, deformations develop from the undeformed (zero) state, while in the steel part, deformations of the normal cross-section are superimposed on the already existing deformations opposite to the operational ones obtained at the first stage of the combined structure during its manufacture.

Keywords: steel-reinforced concrete, cold-formed steel profiles, rod, biaxial load, strain.

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Introduction.

The problem of designing steel-reinforced concrete structures under biaxial loading lies in the complexity of modelling the interaction between the steel and concrete components, which complicates accurate forecast of their combined behaviour under load. The key issues in such calculations include accounting for the nonlinear response of materials, deformations, concrete creep, as well as the absence of a unified and standardised design approach.

Review of the research sources and publications

steel-reinforced concrete structures are characterised by high carrying force, life performance, and efficiency due to the joint action of steel and concrete. Under complex deformation conditions, these structures demonstrate specific features of their stress-formed condition, which continue to be the subject of theoretical and experimental research [1]. The use of composite steel-reinforced concrete floor systems makes it possible to significantly increase structural stiffness and complex loads, particularly horizontal loads, which is essential for high-rise and industrial buildings [2].

In research practice, considerable attention is paid to the mechanics of interaction between steel and concrete. Under loading - especially bending, torsion, compression, and combined deformation modes - there is a redistribution of stresses between the materials, influence of composite solutions, types of attachment, and anchorage solutions [3]. Both the construction stage and the operational stage of the structure are marked by a complex stress - strained state [4]. Instability before the concrete component reaches its full strength may lead to local losses of stability and deformation effects, particularly when precast slabs are used [3]. Not all of the shear-connection surface participates in force transfer; this depends on the geometry of corrugated sections and the arrangement of shear connectors, which significantly affects stress distribution and cracking [5].

Difficulties in designing also arise under long-term loading: creep and shrinkage of concrete reduce the stiffness of the cross-section, increase deflections, and promote cracking, which must be considered in accordance with modern design standards [6].

It is essential to take into account nonlinear and plastic deformations of the concrete component, as well as shear and tensile forces transferred between the materials. To use full stress–strain diagrams of the materials, nonlinear calculation methods are applied, in particular the finite element method (FEM) [7].

In accordance with current standards (in particular DBN V.2.6-160:2010), the design of steel–reinforced concrete structures is performed using the limit state method, taking into account the strain diagram, the interaction of materials, and long-term effects [8].

Definition of unsolved aspects of the problem

Thus, research is still ongoing to improve calculation models and the regulatory framework in order to more adequately account for material interaction and concrete, cracking, the development of residual strains, and the long-term change in material states, taking into consideration the results of experimental studies [9, 10].

Problem statement

The purpose of this work is to present the theoretical relationships for determining relative strains in the cross-sections of steel-reinforced concrete composite structures with cold-formed steel profiles under biaxial loading.

Basic material and results

The article describes the determination of relative strains in the cross-sections of composite steel-reinforced concrete structures with prestressing of the steel part of the cross-section. The steel part of the stem’s cross-section is a U-shaped profile filled with concrete. The creation of initial upward curvature, opposite to the service curvature, explains the increase in the load-carrying capacity of such prestressed composite steel-reinforced concrete structures. By selecting optimal parameters of the initial curvature of the steel part of the beams and the rational stiffness ratio between the steel and concrete components, it is possible to increase not only the stiffness of the composite structure but also its load-carrying capacity.

The prestressing procedure for the steel part of the cross-section is as follows. At the first manufacturing stage, an initial curvature opposite to the service curvature is created in the steel part of the beams using mechanical jacks (see Fig. 1a). At this stage, normal-section strains opposite to the service strains are formed in the steel beam: the bottom fibers are compressed and the top fibers are tensioned.

At the second manufacturing stage, the inner cavity of the U-shaped steel section is filled with concrete (see Fig. 1b). During concreting and throughout the period required for the concrete to reach its design strength, the jacks remain in place under the steel beams. Therefore, the stress-strain state of the steel beams does not change compared to the first stage (the bottom fibers remain compressed and the top fibers tensioned), while the normal-section strains in the concrete are equal to zero. To ensure the subsequent composite action of the steel and concrete parts of the cross-section, rigid anchorage devices are pre-welded to the inner side of the steel section.

At the service loading stage (the third stage), the composite steel-reinforced concrete cross-section works in full composite action (see Fig. 1c). In the concrete part, the strains develop starting from an undeformed (zero-strain) state, whereas in the steel part, the normal-section strains are superimposed on the existing strains opposite to the service ones that were introduced at the first stage during the structure’s manufacturing**.**

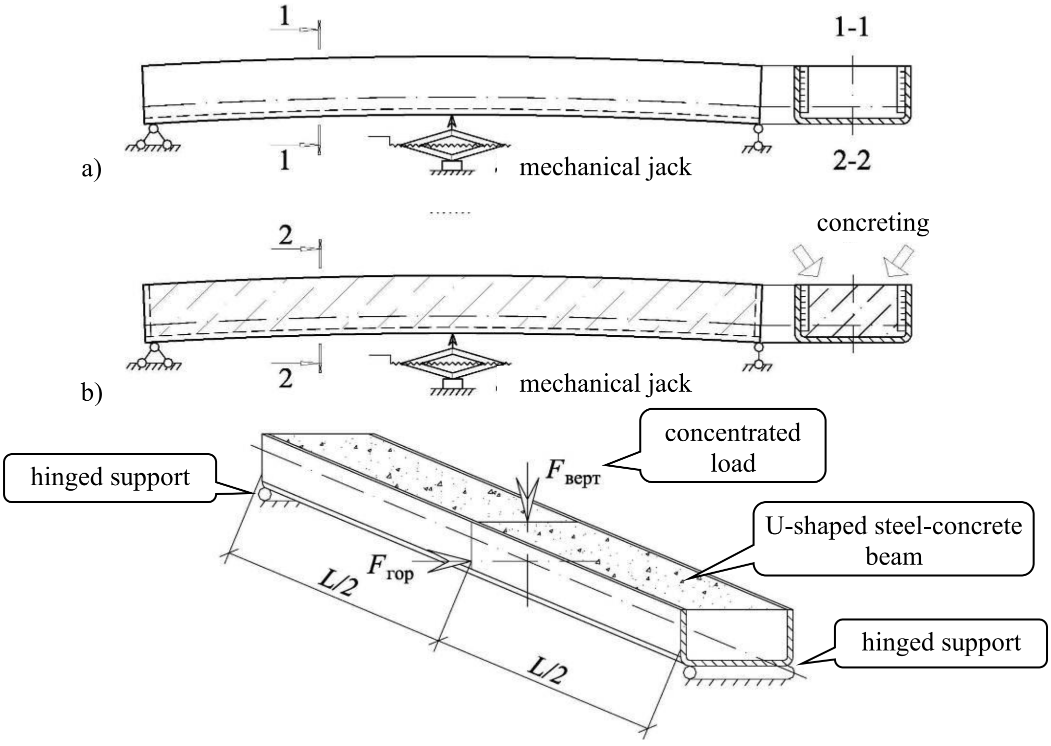


Figure 1 - Schemes of creating a prestressed steel-reinforced concrete structure: a) steel element; b) transformation of the steel element into a steel-reinforced concrete element; c) service loading scheme

Below, we present the relationships for determining the relative strains in the extreme fibers of the cross-sections of prestressed steel-reinforced concrete bar elements under biaxial (oblique) bending.

At the first and second stages of behavior during the manufacturing of steel-reinforced concrete strcutures, the steel cross-section is subjected to curvatures opposite to the service ones, while the strains in the concrete remain equal to zero. In this case, the curvature of the steel part develops only with respect to the horizontal plane. Therefore, the strains in the steel part of the cross-section can be determined using the following formula:

$$\varepsilon_1^{steel} = \varepsilon_2^{steel} = \pm \frac{M_{pr} \cdot y_p}{EI_{st_X}} . \quad (1)$$

The strains in the concrete are equal to zero:

$$\varepsilon_1^{concrete} = \varepsilon_2^{concrete} = 0 . \quad (2)$$

At the third (service) stage, under the action of the service net load, the composite steel-reinforced concrete cross-section works in full composite action. In the concrete part, the strains develop starting from an unstressed (zero-strain) state, while in the steel part the strains are superimposed on the existing strains opposite to the service ones, introduced during the first stage of manufacturing.

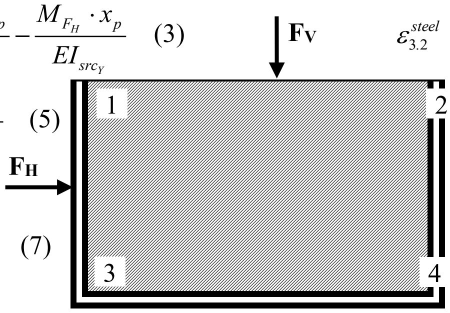
The relationships for determining the relative strains at the extreme points of the cross-section formed at the first two stages of the prestressed steel-reinforced concrete structure under biaxial bending are shown in Figure 2.

$$\varepsilon_{3.1}^{steel} = \frac{M_{pr} \cdot y_p}{EI_{st}} - \frac{M_{F_V} \cdot y_p}{EI_{src_X}} - \frac{M_{F_H} \cdot x_p}{EI_{src_Y}} \quad (3)$$

$$\varepsilon_{3.2}^{steel} = \frac{M_{pr} \cdot y_p}{EI_{st}} - \frac{M_{F_V} \cdot y_p}{EI_{src_X}} + \frac{M_{F_H} \cdot x_p}{EI_{src_Y}} \quad (4)$$

$$\varepsilon_{3.1}^{concrete} = -\frac{M_{F_V} \cdot y_p}{EI_{src_X}} - \frac{M_{F_H} \cdot x_p}{EI_{src_Y}} \quad (5)$$

$$\varepsilon_{3.2}^{concrete} = -\frac{M_{F_V} \cdot y_p}{EI_{src_X}} + \frac{M_{F_H} \cdot x_p}{EI_{src_Y}} \quad (6)$$



$$\varepsilon_{3.3}^{concrete} = \frac{M_{F_V} \cdot y_p}{EI_{src_X}} - \frac{M_{F_H} \cdot x_p}{EI_{src_Y}} \quad (7)$$

$$\varepsilon_{3.4}^{concrete} = \frac{M_{F_V} \cdot y_p}{EI_{src_X}} + \frac{M_{F_H} \cdot x_p}{EI_{src_Y}} \quad (8)$$

$$\varepsilon_{3.4}^{steel} = -\frac{M_{pr} \cdot y_p}{EI_{st}} + \frac{M_{F_V} \cdot y_p}{EI_{src_X}} - \frac{M_{F_H} \cdot x_p}{EI_{src_Y}} \quad (9)$$

$$\varepsilon_{3.4}^{steel} = -\frac{M_{pr} \cdot y_p}{EI_{st}} + \frac{M_{F_V} \cdot y_p}{EI_{src_X}} + \frac{M_{F_H} \cdot x_p}{EI_{src_Y}} \quad (10)$$

Figure 2 - Relationships for determining the relative strains at the extreme points of the cross-section of a prestressed steel-reinforced concrete structure under biaxial bending

In formulas (1)–(10), the following symbols are adopted:

ε^{steel} – relative strains in the steel part of the cross-section;

$\varepsilon^{concrete}$ – relative strains in the concrete part of the cross-section;

M_{pr} – bending moment caused by the prestressing of the steel part of the cross-section;

M_{F_V} – bending moment from service loading in the vertical plane;

M_{F_H} – bending moment from service loading in the horizontal plane;

EI_{st_X} – bending stiffness of the steel part of the structure's cross-section with respect to the horizontal centroidal axis *x*;

EI_{src_X} – bending stiffness of the steel–reinforced concrete structure with respect to the horizontal centroidal axis *x*;

EI_{src_X} – bending stiffness of the steel–reinforced concrete structure with respect to the vertical centroidal axis *y*;

x_p; y_p – coordinates of the point.

The strain distribution diagrams in the cross-sections of the prestressed steel–reinforced concrete structure under biaxial bending are shown in Figure 3. In this case, the loading scheme of the beam is presented in Figure 1: a simply supported beam on two hinged supports, loaded at midspan by a concentrated load.

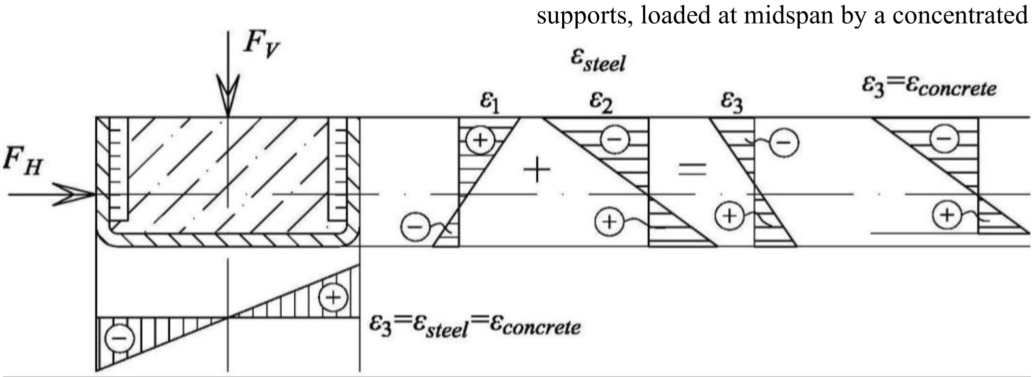


Figure 3 – Sketches of the relative strain distributions in the cross-sections of the prestressed steel-reinforced concrete bar structure under biaxial bending (for the support and loading scheme of the structure, see Fig. 1).

The results of experimental studies of the prestressed steel-reinforced concrete te bar elements manufactured according to the method described above confirmed the theoretical statement [10]. Figure 3 shows the general view of the steel-reinforced concrete bars during testing, with the location of the loading node indicated.

The relative longitudinal strains of steel and concrete were measured in the zone of the maximum bending moment (at midspan) and at a distance of 0.25 of the span length from the supports using electrical resistance strain gauges with a 20 mm gauge length. To control the strains in the most compressed and most tensioned fibers of the specimen, mechanical Huggenberger tensometers with a 20 mm gauge length and a graduation value of 0.005 mm were installed, which ensured a measurement accuracy of relative strains equal to 25×10^{-5}.

Dial indicators were used to measure the deflections at midspan and at a distance of 0.25 of the span length from the supports.

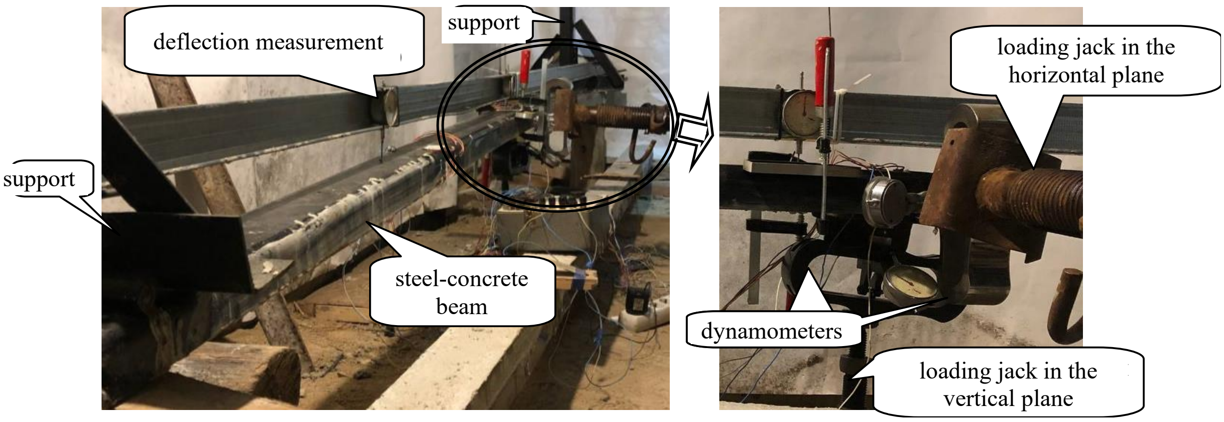


Figure 4 – General view of the steel-reinforced concrete rete beams during testing

Conclusions

The prestressing of bent steel-reinforced concrete structures, taking into account genetic nonlinearity, has been researched using the example of simply supported prestressed bar elements subjected to biaxial bending. The theoretical relationships for determining the stresses at the extreme points of the cross-sections of steel-reinforced concrete bar strucutures with cold-formed steel profiles under biaxial bending have been presented. The results of experimental studies of prestressed composite bar elements manufactured according to the method described above confirmed the theoretical assumptions. The experiments demonstrated the effectiveness of the two-stage manufacturing technology for creating initial counter-bending in simply supported prestressed steel-reinforced concrete bar structures subjected to biaxial bending.

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Розрахунок сталезалізобетонних конструкцій із холодноформованих сталевих профілів при двовісному навантаженні

Аннотація. Проблема розрахунку сталезалізобетонних конструкцій при двовісному навантаженні полягає в складності моделювання взаємодії між сталевою та бетонною складовими, що ускладнює точне прогнозування їхньої спільної роботи під навантаженням. Тривають дослідження для вдосконалення розрахункових моделей і нормативної бази для більш адекватного обліку взаємодії й бетону, тріщиноутворення, розвитку залишкових деформацій та тривалої зміни стану матеріалів, враховуючи результати експериментальних досліджень. Метою роботи є наведення теоретичних залежностей визначення напружень у крайніх точках перерізу стержневих сталезалізобетонних конструкцій із холоднодеформованих сталевих профілів при двовісному згинальному навантаженні. Сталева частина перерізу розглядуваного стержня являє U-подібний профіль, який заповнюється бетоном. У бетонній частині деформації розвиваються від недеформованого (нульового) стану, у той час у сталевій частині деформації нормального перерізу накладаються на вже існуючі протилежні експлуатаційним деформації, отримані на першій стадії роботи комбінованої конструкції під час її виготовлення. Результати експериментальних досліджень виготовлених за описаною вище методикою попередньо напружених сталебетонних стержневих елементів підтвердили теоретичні положення.

Ключові слова: сталезалізобетон, холоднодеформовані профілі, стержень, двовісне навантаження, деформації.

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