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Experience and current issues of designing of steel and concrete composite structures of roof and floor systems

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The current state of the building covering structures is thoroughly investigated, in particular, the world experience in the construction and building of various roof and floor structures, made of various materials, including composites, has been studied. A thorough results analysis of theoretical studies and experimental tests on the constructive solutions effectiveness determination conducted by domestic and foreign scientists has been carried out. Based on the received information about the features of the construction and technological solutions, there were determined the advantages and disadvantages of existing construction structures, the prospective development directions. Based on the result of actual scientific and technical literature analysis, the main research objectives are formulated.

Keywords: steel and concrete composite structures, a roof, a floor, a permanent shuttering, cross-sections

Досвід і проблеми проектування сталезалізобетонних конструкцій покриття та перекриття

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Досліджено сучасний стан будівельних конструкцій покриття й перекриття, зокрема вивчено світовий досвід проектування, конструювання та будівництва таких конструкцій, у тому числі виготовлених із різних матеріалів. Виконано ґрунтовний аналіз результатів теоретичних досліджень та експериментальних випробувань щодо визначення ефективності конструктивних рішень покриття й перекриття, виконаних вітчизняними та зарубіжними вченими. Оскільки сталезалізобетонні конструкції зазнають бурхливого розвитку, модифікуються й удосконалюються, то вивчено проблему їх ефективності на всіх етапах життєвого циклу та проектного ресурсу. Проаналізовано новітні підходи до проектування сталезалізобетонних конструкцій покриття й перекриття. На підставі отриманих відомостей про особливості будови й технологічних рішень, переваги та недоліки існуючих конструкцій покриття й перекриття визначено перспективні напрями їх розвитку. У сталезалізобетонних конструкціях покриття й перекриття раціонально та повною мірою використовуються характеристики міцності матеріалів, тобто сталеві елементи розташовуються в зоні дії зусиль розтягу, а бетон – у зоні дії зусиль стиску. Такий поділ і розмежування різнорідних матеріалів вимагає заходів із забезпечення їх сумісної роботи. Сьогодні найбільш ефективним способом об'єднання сталевих деталей та бетону є застосування різноманітних анкерів: жорстких, гнучких і комбінованих. У загальному випадку несуча здатність сталезалізобетонних конструкцій, за винятком трубобетонних та схожих за будовою елементів, визначається саме несучою здатністю анкерних засобів на зріз і зсув. З огляду на зазначене останнім часом усе частіше при розробленні нових конструктивних рішень сталезалізобетонних елементів застосовується спосіб забезпечення сумісної роботи, суть якого полягає в об'єднанні сталевих каркасів із залізобетонними елементами в процесі бетонування без використання анкерів, тобто сталева конструкція забетонується. Такий підхід дозволяє отримати цілісну, неподільну конструкцію, несуча здатність котрої залежить від несучої здатності залізобетонних та металевих елементів.

Ключові слова: сталезалізобетонна конструкція, покриття, перекриття, незнімна опалубка, переріз



Introduction

Steel and concrete structures are designs that have a long story of development, a wide scope, advantages, and shortcomings compared to other designs types. The scope and rate of such designs development are closely related to the significant amount of their features and difficulties caused by them. A part of the challenges concerns the design, construction, and further steel and concrete composite structures service, another part relevant to their structural concept features. All this demands the detailed and thorough analysis of the experimental and theoretical studies results, and obtained data synthesis with the purpose of establishing a shared understanding of steel and concrete composite structures stressing features, and further research trends allocation. Steel and concrete composite structures is a widespread composite material that is made of a concrete mix, and filler, and includes steel elements and reinforcement. Steel and concrete composite structures can be strengthened with rods, rigid and external reinforcement; also, they can be reinforced with different steel sections: tubes, plates, corners, steel sheets, etc.

Studying the stress-strained state, the search for effective ways of achieving steel and concrete members combined action, optimization, and design improvement taking into account the last achievements in science and technology are the main steel and concrete composite structures research trends.

A combination of positive reinforced and steel structures' physic-mechanical properties with simultaneous disposal of their shortcomings is the main advantage of steel and concrete composite structures.

Refer to the increased rigidity and bearing capacity unlike other designs to advantages of steel and concrete composite structures.

The finding of positive characteristics is the criterion that defines the structure efficiency. Therefore, in the steel and concrete composite structures, it is possible to reach a favorable strength indicator combination as steel during stretching as concrete on compression thanks to their combined action. The efficiency of such association is known and the application expediency in construction is proved and recognized long ago.

Thanks to such connections, steel and concrete composite structures are characterized by reduced sensitivity to damages and defects compared to reinforced concrete or steel. Besides, an established fact that they are capable of sustaining considerable loadings, even after achieving the yield point by the reinforcement. Also, treat steel and concrete composite structures advantages: high bearing capacity; low construction height; resistance to dynamic influences; technological effectiveness.

The steel and concrete composite structures designs are extremely various therefore they can be classified by different signs: for example, on kind of structures behavior, a way of production, or construction.

Also, steel and concrete composite structures can be classified by structural element type: supports or columns with the side hollows filled with concrete, and with external and internal rigid reinforcing; beams or crossbars with the side hollows filled with concrete,

and with external reinforcement with steel flat strip, and internal rigid reinforcing, including reinforced concrete structures with a permanent shuttering; the precast and monolithic steel and concrete composite slabs, including slabs with the metal decking or orthotropic plates, or with a steel frame; the reinforced combined concrete structures reinforced or strengthened by lattice, rod or other steel elements; the rafter combined steel structures with the reinforced concrete elements; elements of the spatial combined structures; elements of high-rise buildings and constructions; elements of long-span constructions, bridges, platforms, etc.; other special and engineering constructions and elements.

Steel and concrete composite structures gained the biggest distribution in bridge construction, and civil engineering. Steel and concrete composite structures in construction of buildings and structures are effectively used as a column, slabs, beams, crossbars, etc. Increasingly design features, properties, and resistance to damages and defects define the scope of steel and concrete composite structures.

However, it should be noted corrosive environments limit the steel and concrete composite structures scope.

It is known that corrosion of the steel and concrete composite structures open and unprotected steel parts and surfaces is one of the most frequent reasons for damages, which significantly reduce bearing capacity and affect the structure service suitability and durability.

Review of the research sources and publications

Quite often steel members carry out the role of permanent shuttering. Steel and concrete composite structures as material are not new and the fact that it has high technical and economic rates is known for a long time, therefore, he didn't lose its relevance and presently is intensively investigated around the world [1–3].

In most cases, steel and concrete composite structures have the highest technical and economic effects compared to other structures [4].

Analysis of the sources showed that they are devoted to detailed individual problems research, but there are reviews devoted to the data generalization [5–8].

Definition of unsolved aspects of the problem

Because steel and concrete composite structures experience rapid development around the world, are constantly modified and improved there was the obtained data analysis and synthesis problem. This problem is urgent as its solution will allow considering in a complex all factors at all life cycle stages in a particular design, building and service, the feature of behavior under load, and the stress-strain state.

Problem statement

Study an experience and current issues of steel and concrete composite structures designing of roof and floor systems.

Basic material and results

Steel and concrete composite structures are a special building structures class that found application in modern construction. As is known, a balance between the non-concreted steel members bearing capacities and concrete steel members belonging to the same structure is the feature that distinguishes steel and concrete composite structures from other structures.

At the steel and concrete composite structures design obviously, there is what their intense deformed state depends on physic-mechanical materials properties, which are their part, namely steel, and concrete. Steel is a uniform material, therefore, it has constants, within a class, physical and mechanical properties, as for concrete, they are very different in the physical and mechanical properties. The physical and mechanical concrete properties depend on its structure, which has the ability to change over time that in total under action external loadings cause the creep concrete deformation. Also, the concrete structure is affected by changing stresses and formatting of their concentration owing to communications between particles of concrete collapse. At compression, there are longitudinal compression stresses and cross stretching stresses from which action concrete collapses.

Except for material selection with necessary physical and mechanical properties, additional complexity at the design of steel and concrete composite structures, there is a problem of ensuring the combined action of concrete and steel. The combined action of these materials is ensured by coupling among themselves, only in that case materials will be deformed and work in common. The triaxial stress state availability is the most favorable condition under which it is possible to reach the necessary coupling between concrete and steel elements. This state is a well-known tube-concrete element characteristic where concrete is in a steel cage. Unlike tube-concrete elements, the special shear connectors application for the steel and concrete composite structures majority is a typical solution for the steel and concrete combined action problem.

In general, many studies of scientists from different world countries are addressed to studying this issue. There are the largest shear connectors species, but the most typical and modern decisions into known shear connectors are short steel rods with a cap at the end – a headed stud shear connector (Fig. 1a) [9].

It should be noted the shear connectors can have various configurations and are produced practically from any steel fragment, a detail, or a plate (Fig. 1b).

Except for the typical design, shear connectors can be as a rigid connector (Fig. 1c, d), as loops (Fig. 1e, f); made from steel rods (Fig. 1g, h). The way of placement of shear connectors depends on the service of structures, and efforts that arise under loading. In order for the shear connector to be a flexural member, it must be placed perpendicularly, and if it is placed at an angle of 45° in the direction of the shear force, it will be in tension.

The type choice and shear connectors shape depends on the shear connectors' simplicity, also their ability to be connected to the steel parts and elements by welding,

and service conditions of the structure. As already mentioned, the most widespread types of shear connectors are headed stud shear connectors (Fig. 1a) and shear connectors made from short steel rods (Fig. 1g, h). Except for the basic purpose – to combine steel and concrete, the shear connectors can carry out the role of transverse reinforcement in designs with external reinforcement.

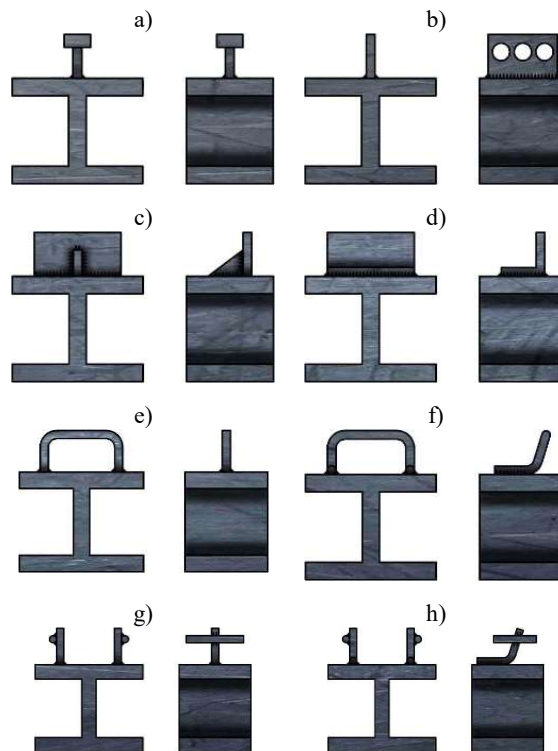


Figure 1 – Certain types of shear connectors:

- a – headed stud shear connector;
- b – shear connector made of the perforated plate;
- c – rigid connector; d – flexible connector;
- e – vertical loop; f – inclined loop;
- g – vertical bar; h – inclined bar.

Usage of various glue substances [10] is the less known way for ensuring combined action of steel and concrete structure parts.

A different important issue that is closely linked to the steel and concrete composite structures design is the assessment and rationing of their technical conditions. The relevance of the search for the solution to this problem is especially accurately outlined against the background of the actual wear and obsolescence of fixed assets of production, economic, educational, and other institutions. On the other hand, the importance of the solution of this problem predetermines the fact that designs are improved and developed more intensively, than methods of their calculations, and there are no standard recommendations and provisions, which regulate a technique of steel and concrete composite structures technical condition estimation. A bigger measure of the technical states concerns objects rationing questions, which are operated, but also does not lose the sharpness on the relation and to new construction. For new construction, definitions of a steel and concrete composite structures design resource are a current

problem also. There are recommendations concerning the definition of a steel and concrete composite structures design resource according to which at the steel and concrete composite structures design operational suitability indicators are set with a stock [11].

The specified technique provides acceptance of the steel service strategy and concrete composite structures and the resource coefficient introduction [11].

The service strategy of steel and concrete composite buildings and constructions or their members provides two options: 1) without capital repair throughout all characteristic terms of service; 2) carrying out capital repairs. The approach described in the paper [11], gives the chance to consider a time factor and allows optimizing construction and service structures costs.

Today the international bearing structures experience of construction from steel and concrete composite structures incredibly various also contains a significant amount of different objects, buildings, and structures in all construction fields. Despite universality and a variety of steel and concrete composite construction elements, the most frequent application they found was in industrial and civil engineering, especially in the floor structures.

Steel and concrete composite beams, which consist of a reinforced concrete plate, and a steel beam (Figure 2a) belong to the most widespread steel and concrete composite structures types. Scientists of the Frits laboratory of Lehigh University conducted thorough such designs research in the middle of the last century in the USA. The research results testify to high strength and technical and economic rates.

In such structures, the combined action of a steel element and reinforced concrete plate can be provided with different shear connectors types, but in terms of effective action conditions under shear forces, rather with rod shear connectors and connectors made of separate corner pieces, shear connectors as inclined loops are better and ensure combined elements action practically until the total structure break [12].

Steel beams with a reinforced concrete top belt (Figure 2b) are a kind of steel and concrete composite beams. The structures application reduces by 15 % cost and for 35 % labor of installation and construction [13].

Steel and concrete composite beams that have external reinforcing with a sheet (Figure 3) are one more kind of composite structure made of steel and concrete. Such structures can have both a rectangular shape of section (Figure 3a, b) and T-type (Figure 3c), besides, they can be box-type. The bearing capacity of a steel and concrete composite box-shaped type beam compared to analogs, depending on the accepted reinforcing way is 2-6 times more [14].

To increase the rigidity and bearing capacity of the T-type steel and concrete composite beams, it might also be reinforced with tubes (Figure 3d) [15,16].

The steel and concrete composite beams usage that reinforced externally with sheet compared to typical reinforced concrete beams assists economy of high-strength longitudinal armature up to 20 % and 25 % at single and double reinforcement in construction respectively, and the structures advantage, which made steel

entirely lies in the steel economy of up to 35 % at identical bearing capacity [17]. The resistance to damages compared to the beams made of different materials and the fact that steel and concrete composite beams at similar damages have greater durability than reinforced or entirely steel structures is one more steel and concrete composite beam advantage. However, the structure's bearing capacity depends on service conditions and the mode of loading. Because of an experimental study of the influence of short-term cyclic and sign-variable loads on durability and deformability of steel and concrete composite beams, it is established that the bearing capacity decreases up to 20 % compared to the bearing capacity of beams at single loading. Besides the bearing capacity depends on the total number of cycles of loading and the level of the previous loading by negative bending moment [18].

In most cases, steel elements play a role in steel and concrete strengthening composite structures, but there are also such structures where this role is played by concrete. Beams that are formed from steel elements with the hollow (Figure 4) filled with concrete belong to such structures. The concrete coupling with a beam can be reached both using different shear connectors and using adhesives. In general, steel and concrete composite beams are highly bearing capacity. Experimental studies showed that the bearing capacity of the beams thanks to concrete in hollow increases compared to typical steel beams of a similar profile by 30-40 % in bend and for 40-50 % in shear [19].

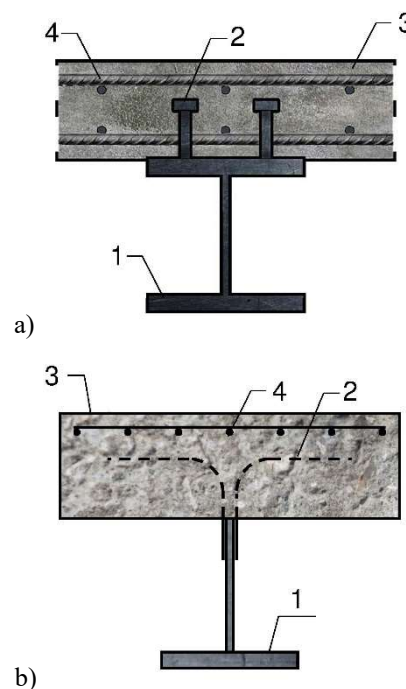


Figure 2 – Types of steel and concrete composite beams:

- a – a structure that consists of a reinforced concrete plate and a steel beam;
- b – a steel combined beam that held a reinforced concrete top flange;
- 1 – steel beam; 2 – shear connector;
- 3 – concrete slab; 4 – reinforcement.

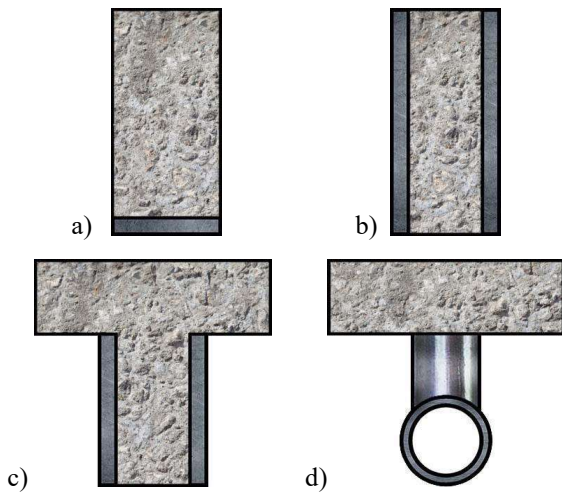


Figure 3 – Types of the cross-sections of steel and concrete composite beams:
 a – with external horizontal reinforcing;
 b – rectangular with external vertical reinforcing;
 c – T-type; d – type with reinforcing by a steel tube.

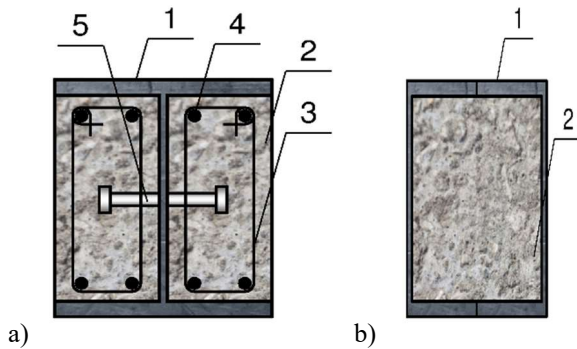


Figure 4 – Steel and concrete composite beams with the hollows filled with concrete:
 a -- beam with an open profile;
 b -- beam with a closed profile;
 1 – rolled steel; 2 – concrete;
 3, 4 – crosswise and longitudinal reinforcing;
 5 – shear connectors.

Composite structures, which consist of monolithic plates coupled to steel sheets (Figure 5) are widely used. Their main advantage is the small height of the cross-sections that are within limits of 2.5...5 % of their length, however, the bearing capacity of such steel and concrete composite plates at different consolidation ways significantly depends on the steel sheet thickness. It is experimentally established that the bearing capacity increases correspond to the increase in the thickness of a steel sheet [20].

Such structures were extremely often applied in high-rise construction as the bearing horizontal systems in recent years [21]. They were used in large quantities in the USA in the middle of the last century. Over time such systems began to be applied in Europe, in particular in Great Britain, began to consider a steel part of a structure (the pro-thinned-out flooring) not only as a permanent shuttering but also as external reinforcement [22]. In this case, there is a perception problem design

of the horizontal shifting efforts and to the prevention of separation of concrete from the sheet. At different times this issue was resolved differently, at first combined steel sheet and concrete action was reached thanks to the special sheet shape [23] over time began using the corrugated steel sheet with the drawing on the side [24]. In recent years the combined systems that can be formed from the special shape sheet with the applied relief image, reinforcing grids, and different fibers are actively investigated [25, 26].

To carry out these experimental studies and establishment of strength characteristics of steel and concrete composite slabs there were used samples with sizes of 1×1 m and 50 mm high. The steel sheet thickness varied within 1...3, 5 mm.

Considering good strength characteristics the most effective way is an application of special shear connectors that join steel elements by means of welding [27], but there are cases when such a shear connector could not apply or it is not economically expedient. Then non-standard structural concepts can serve as their alternative. An example of such shear connectors are items that are connected to the beam differently. Such shear connectors are produced as cold-formed steel Z or C-sections, which are connected to the beam with bolts or self-tapping screws.

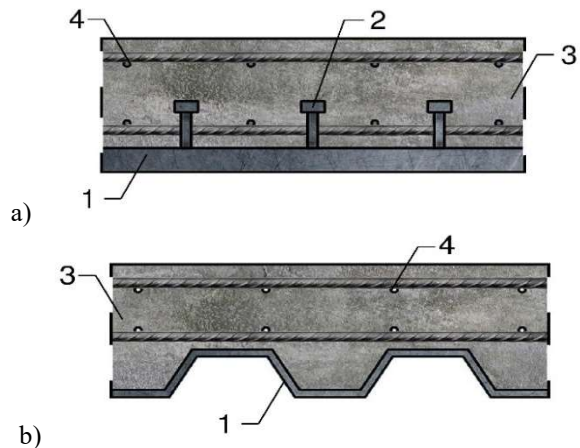


Figure 5 – Steel and concrete composite floor systems that consist of reinforced concrete slabs coupled to steel sheets:
 a -- orthotropic sheet; b -- steel sheet;
 1 – sheet; 2 – shear connector;
 3 – concrete; 4 – reinforcing.

The thin-walled composite slim-floor systems are a kind of such design. Their structural concept is in applying an innovative composite connection. This connection is reached by making reinforcing bars through openings in beams. Such technology is economic and effective as it is possible to use the full concrete elements potential. Results of experimental studies under the action of different loadings types, including dynamic and vibration, which demonstrate the increased bearing capacity and rigidity of such designs compared to analogs for 100 and 150 % [28] are confirmation to it.

Other steel and concrete composite structures representatives are a beams system with a box-shaped Δ -similar cross-section [29]. The beam's feature is opening with a diameter of 75 mm or 150 mm, which is regularly distributed in length in a certain opening quantity with the edges bent inside. Thanks to the availability of such openings with curved edges, the materials combined action are ensured. Such beams can be applied both with combined thin-walled (Figure 6a) and with typical reinforced concrete hollow slabs (Figure 6b) [30].

The structures, which include slabs that consist of the profiled steel sheets and the spatial framework made of reinforcing bars as a lattice [31] are one more kind of steel and concrete composite bearing system.

The systems have many advantages, such as profitability, convenience, and safety that allow them to reduce construction terms considerably compared to other systems. The structure can maintain the considerable concrete and construction equipment weight and is set directly on steel beams without additional support details [32]. Also, monolithic slabs with the profiled steel sheet can be mounted on different substructures or support structures like beams, crossbars, farms, etc. Besides the substructures can be reinforced concrete, steel, or steel-concrete. The steel and concrete composite slabs in association with steel farms or steel beams are an example of such a structure. Moreover, the design of the top knots can be diverse, most often applying steel rolled sections and thin-walled steel structures to the systems top belt production.

In research [33] a similar design is considered by the length of 44 m which is made of a spatial farm and a concrete slab. The finite element method is applied to

the theoretical analysis of the composite structure behavior. The results show that the concrete slab, when it is in combined action with the composite space truss, is compressed curved, and the internal forces in the composite truss elements are distributed evenly, thus, the materials strength properties are effectively used.

The interesting constructive concept is a system with usage of the steel tubes filled with concrete. This system consists of a monolithic slab that is connected to a profiled steel sheet, it sets over the truss with parallel belts where the top belt is filled with concrete [34, 35]. The steel and concrete composite slab can be lying as in the steel tube plane filled with concrete, (Figure 7) as on the steel tube top filled with concrete (Figure 8). In addition, according to the first scheme, the combined steel and concrete members action between themselves is implemented due to contact of a tube and concrete, and for the second, it is due to the shear connectors application. Experimentally it is proved that the structures have an increased bearing capacity.

The dependence between the failure load level (the load when the connection between concrete and steel members is lost) and a concrete class durability and concrete top layer thickness is established. It is established that at the increase in a concrete durability class the failure load for the first scheme increases up to 45 %, and for scheme 2 – up to 33 %. Besides, the shifting effort for the first scheme is almost four times more, than for scheme 2. Depending on the concrete top layer thickness, the failure load for the first scheme increases by up to 21 %, and for the second scheme – up to 26 % [36].

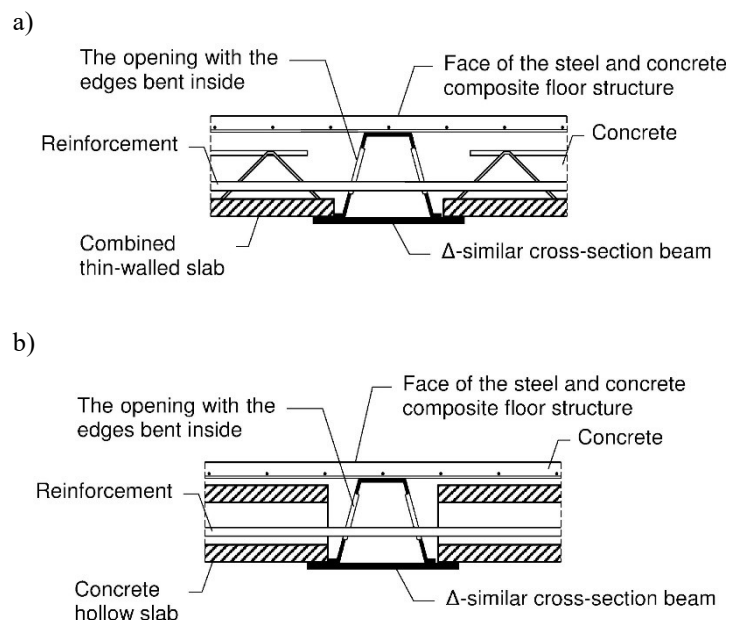


Figure 6 – Steel and concrete composite systems consist of Δ -similar beams and thin-walled (a) or hollow slabs (b) [29, 30].

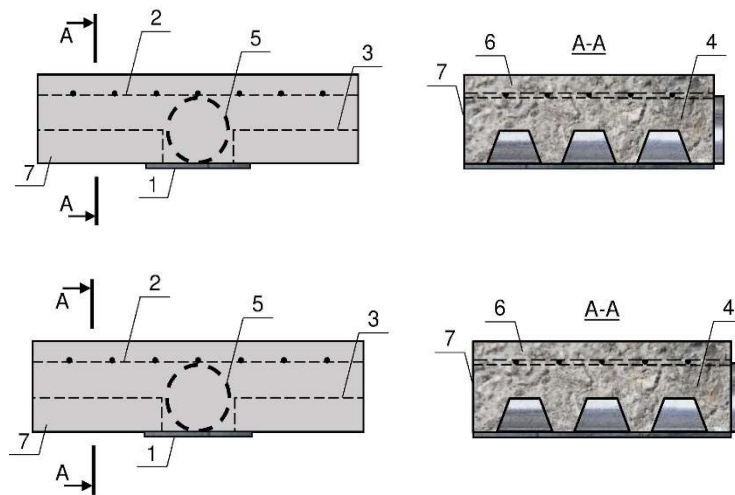


Figure 7 – The structure with a monolithic steel and concrete composite slab that is lying in the plane of the tube filled with concrete [35]:

1 – steel basic deck; 2 – reinforcing grid; 3 – the profiled steel sheet; 4 – concrete; 5 – the steel tube filled with concrete; 6 – the top layer of concrete; 7 – the face of the plate.

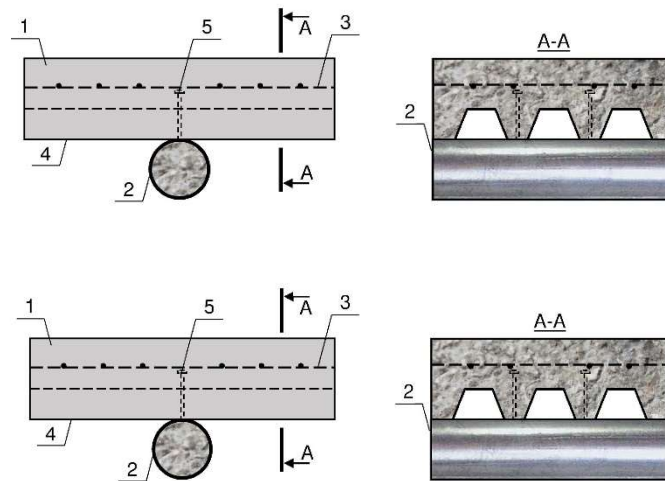


Figure 8 – The structure with the monolithic steel and concrete composite slab that is lying on the tube filled with concrete [35]:

1 – concrete; 2 – the steel tube filled with concrete; 3 – reinforcing grid; 4 – the profiled steel sheet; 5 – shear connector.

Along with the monolithic steel and concrete composite structures research, combined steel and concrete composite precast systems are studied. The combined structures use is the perspective direction for improving structural concepts of the bearing steel and concrete composite systems.

The slab with a steel frame (Figure 9) is one of the combined steel and concrete composite structure elements. It is experimentally established that the bearing capacity of such slab compared to a reinforced concrete slab of a similar section is more on 45–50 % [37]. Besides, due to a steel frame, the slab has increased rigidity.

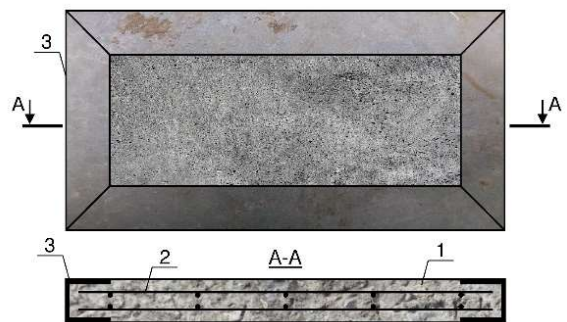


Figure 9 – The slab with a steel frame for the system of the precast flat slab construction [37]:
1 – concrete; 2 – reinforcing grid; 3 – steel frame.

It should be noted that the slab framed with steel members, except the key qualitative physic-mechanical parameters, has technological advantages, it is the low labor of production that is reached due to the frame use as a permanent shuttering. Experimentally confirmed advantages of such plates give the chance to apply them in the flat slab construction.

Other examples of the complex roof systems type are structures that consist of typical ridge reinforced concrete slabs and steel trusses. While the application of that structure the materials economy is reached if the combined action between slabs and trusses is provided. If trusses by the length of 30 and 36 m and slabs of 6 and 12 m are used, the steel economy reaches up to 18 %, concrete – up to 10 % [38], and in case of application of the long-span light grid steel and concrete composite slabs, the steel economy increases up to 25 % [39]. Among rod steel and concrete composite rafter designs, some consist of reinforced concrete beams and steel farms.

In general, the inclusion of typical reinforced concrete elements in combined action as the top belt with typical steel farms is an economically justified design. Even though these structures are effective, they have also essential shortcomings: firstly, it is the design complexity and the need for typical elements adaptation under new service conditions.

In general in industrial and civil engineering the technical and economic effect promotes the steel economy up to 33 % rather than entirely metal and up to 11 % compared to traditional reinforced concrete structures that have steel and concrete composite elements applications. Besides the given expenses decrease up to 30 % rather with steel and up to 50 % compared to reinforced concrete structures [40].

It is possible to claim efficiency and expediency of steel and concrete composite structures usage in the roof or floor systems construction, leaning on analysis results of current researches, as well as based on the different structural concepts review of the steel and concrete composite bearing elements, and widely used connections between steel and concrete details. However, for this purpose, it is necessary to execute thorough theoretical research of the spatial bearing systems and construction ways for most effective spatial systems allocation, which will be possible to be applied to shaping the roofs.

Conclusions

For achieving the goal, the existing bearing systems and ways their shaping complex review was executed. As the result is the allocation of an among all bearing systems variety of the most effective in spatial behavior terms, low weight, material consumption, and architectural expressiveness, etc. Based on the steel and concrete composite structures review and the theoretical and experimental studies results, it is possible to notice that such structures are effective.

In such structures, materials strength characteristics are rationally and fully used, in general through the steel members are located in stretching elements, and concrete – in compression. Such an entirely different materials combination requires measures for ensuring their combined action.

Today in the most effective steel details and concrete members connection way is applications of different shear connectors: rigid, flexible, and combined. Generally, the steel and concrete composite structures bearing capacity, except for concrete-filled steel tubular structures and similar structures, is defined by the bearing capacity of the shear connectors in shearing or shifting.

Considering specified, for developing new steel and concrete composite systems structural concepts, the way of ensuring combined action between steel and concrete members the essence of which is the combination of a steel frame and reinforced concrete elements together during the concreting without the shear connectors usage is becoming increasingly applied, it means the steel structure is put in concrete solid. Such an approach allows creating integrity and indivisible structure in which bearing capacity depends on the bearing capacity of reinforced concrete or steel elements.

Steel and concrete composite structures have significant advantages and positive properties that allow applying them successfully in the different industrial and public buildings construction. In such structures the efficient materials use concept, and functions distribution is implemented, therefore the structure components are in the stresses that are inherent for them only, which means steel members are in tension, and concrete members are in compression. However, it is necessary to notice that the steel and concrete composite systems also have structural concepts imperfections. First of all, it is the complexity and massiveness of nodal connections. In certain cases, there is a need for shear connectors. It is possible to carry to shortcomings as well that such structures are monolithic, and it considerably limits a scope. In the case of the precast structures industry or on the building site, the span is limited and if concreting is carried out in design position – the construction process technology complexity due to concreting or welding overhead works, the need of timbering installation of, etc is increased.

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