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COMPOSITE AND INTERACTION EFFECTS IN STEEL-CONCRETE STRUCTURES FOR HIGHER FIRE RESISTANCE

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Abstract. Wide application of steel structures for office and industrial buildings is one of the main features of Lithuanian and world building industry. This fact is related to an essentially wider use of new structural solutions, new structural members and materials. Usage of different types of materials in one structural system for better utilisation of positive properties of each component is very popular in current building industry. Composite beams, columns, beams-columns and composite floors can be mentioned. Structures that were designed and erected twenty or more years ago are mostly a collection of different types of structural elements. In general, interaction or composite effect is not taken into account, when designing such structures. Though a considerable number of roofs and ceilings made up of reinforced concrete slabs and steel beams or steel trusses are still in maintenance. Structural solution of the slabs, welding of embedded steel parts of slabs to steel structures, filling with concrete the joints between slabs create the conditions for interaction of slabs and steel structures. The result of this effect is that slabs take up a part of the internal forces of the steel structures and consequently diminish it in steel beams and trusses. It is obvious that this fact leads to the increase of load bearing capacity and fire resistance. The paper deals with the problem of evaluation of composite and structures interaction effect on fire resistance.

Keywords: composite structures, steel beams, reinforced concrete slabs, interaction of structures, fire resistance.

1. Introduction

Wide application of steel structures for office and industrial buildings is one of the main features of Lithuanian and world building industry. Steel structures offer exciting architectural possibilities, quick fabrication and erection, possibility to use steel in combination with other structural materials of high effectiveness. All these advantages lead to cost effective construction.

Type of buildings, their geometrical parameters and installed industrial technologies determine the level of fire resistance requirements of load bearing structures [1, 2]. Fire resistance of structural elements depends on a wide range of different parameters. These parameters can be divided into two main groups.

One group affects the bearing capacity of structural element under fire conditions and related critical temperature [2, 3]. Main mechanical materials properties belong to this group. Modification law for these properties under high-temperature conditions is defined in design codes [3, 4]. A lot of investigations are performed in this field to derive properties-temperature relations. So material behaviour in a high-temperature environment is more or less known. This is true on material level, but not true on structural element or global structure level. On a higher-level of interaction between materials and between it separate structural elements become very important and can have substantial influence on bearing capacity under fire conditions too. In this article we do not discuss the problem of global analysis under fire conditions. We will try to investigate how interaction of different materials and separate structural elements affects the bearing capacity under fire conditions.

The other group of parameters determines the time in which critical temperature will be reached. This time is simply called fire resistance. Thermal properties of materials included in structural element can be assigned to this group. Values of these properties also depend on temperature conditions. Such relations are included in design code [3] and values of properties can be evaluated in the necessary temperature situation. Because steel is very homogeneous material the design code provides simple solutions for determination of section temperature in dependence on section shape and heating situation. For sections made of different materials and with complex shape finite elements method can be used to create section temperature fields for each moment of simulated fire situation. These investigations will be performed in future.

In most cases unprotected steel structures do not fit for fire resistance requirements and effective fire protection materials are still expensive enough. One of the ways to make fire protection cheaper is to choose special types of composite structural elements, which, in some cases, can be used without additional fire protection measures [5, 6]. The other way – the use of more precise evaluation of behaviour of structural elements in case of fire.

Effectiveness of composite structures under fire conditions and the method giving possibility to take into account the interaction of load bearing structures and reinforced concrete slabs under normal and fire conditions, is discussed in the paper.

A great deal of substantial changes in the construction sphere of various types and of different destination buildings in Lithuania took place in recent years. Especially this fact is related to a wider use of new structural solutions, new structural members and materials. Though a considerable number of roofs and ceilings made up of reinforced concrete slabs and steel beams or steel trusses are still in maintenance.

Discussing the problem in question, first of all analysis of the behaviour of roof and ceiling structures composed by reinforced concrete slabs and steel beams or steel trusses has to be made. And then, on the basis of these results, fire resistance of steel structures may be cleared up. The result of the above-mentioned analysis will be a more precise determination of internal forces in the steel structures and consequently a more reliable evaluation of their fire resistance.

2. Composite structures and fire situation

It has already been mentioned that composite section cannot only increase level of strength utilisation of materials from which section is composed, but also provides a higher fire resistance of structural element [5, 6]. Proper decision in the case of composite structure can allow to design high performance structural elements for fire conditions. Some of such solutions can exclude usage of expensive fire protection materials. Structural fire design experience shows that in most cases for buildings with unprotected steel columns and beams fire resistance can be about 15 min. The investigations [6] show that it is possible to reach 60 min fire resistance limit by using composite structural elements without fire protection.

In Eurocode as in almost all national codes for fire design temperature increasing rate depends on section factor:

$$SectionFactor = \frac{A_m}{V}, \quad (1)$$

where A_m is the exposed surface area of the member per unit length; V is the volume of the member per unit length. A higher value of fire resistance can be obtained in case of high V value and low A_m value. Utilisation of bearing capacity (load level) is also important for fire resistance calculations. Main goal for fire resistance in case of using composite floor system is reduction of exposed surface area A_m.

Typical composite beams with shear connectors and concrete floor on corrugated sheet is not a very advanced system for fire situation. In such structural solu-tion only top edge of upper flange of beam can be prote-cted from fire. Unfilled voids between corrugated sheet waves and upper flanges must be protected as well. Otherwise it will reduce floor system fire resistance. Much better effect can be reached by using Slim Floor system (Fig 1, 2). In such systems, special modified I beams with additional bottom plate extending beam flange for supporting deep steel decking are used. ASB or IFB beams are also successfully applied for Slim Floor system.

Another floor type ensuring the same reduced section factor can be arranged from the mentioned types of special beams and prefabricated reinforced hollow concrete plates. In such a system corrugated steel sheets are not used (Fig 3).

Prefabricated plates are placed on bottom flange of beams and top concrete layer with additional reinforcement is used.

Fire resistance of a building depends on fire resistance of all bearing structures. The second important structural element in building skeleton is column. Filling with con-crete space between flanges can increase fire

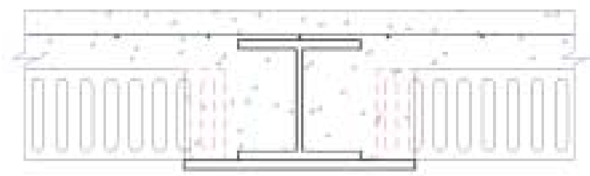

Fig 1. Cross-section of Slim Floor beam with extended bottom flange

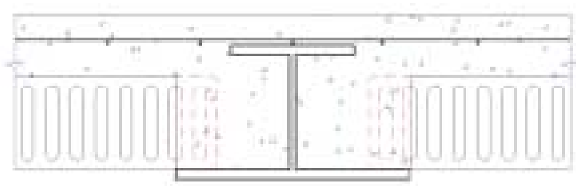

Fig 2. Cross-section of Slim Floor beam with extended bottom flange

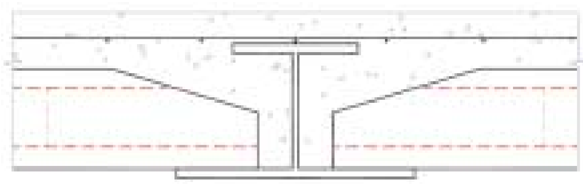

Fig 3. Cross-section of composite floor system with prefabricated plates

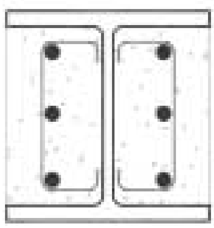

Fig 4. Cross-section of partially encased column

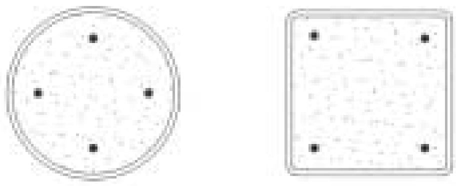

Fig 5. Cross-section of composite columns with additional reinforcement

resistance of steel columns. Concrete must be joined to column body by shear connectors. Reinforced concrete may be used for achieving higher fire resistance (Fig 4). In some cases the same method for increasing the fire resistance of steel beams can be effective. For such beams longitudinal reinforcement bars must be joined with transverse bars welded to beam web.

Fire resistance of effective composite structures with sections from steel CHS or RHS sections can also be increased with simple adding of longitudinal reinforcement (Fig 5). For such sections transverse reinforcement is only necessary to fix bars on proper position.

All described methods for increasing the fire resistance of steel members can guarantee up to 60 min fire resistance depending on the quantity of reinforcement. The required fire resistance level with such measures can be reached much more cheaper in comparison with ordinarily applied special passive fire protection materials. Additional quantity of steel and concrete is necessary when fire resistance of elements must be 30 min or higher.

As it has been mentioned, there exists another possibility to increase the fire resistance. It does not require additional financial resources, but in some situations can ensure necessary fire resistance or reduce the quantity of fire protection materials. Such results can be obtained by using more precise methods for evaluating the internal forces of bearing structures. It may be made taking into account interaction between different structural members.

3. Interaction between slabs and beams

In accordance with the existing design practice reinforced concrete slabs are considered as exterior load

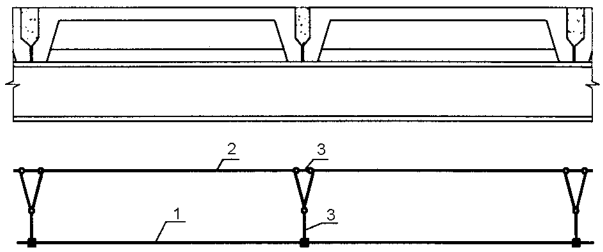

Fig 6. Structural and computational schemes for investigation of beam–slab interaction: 1 – steel beam, 2 – concrete plate, 3 – rigid links

only. On the other hand, really the structural solution of the slabs, welding of embedded steel parts of slabs to the steel structures, filling with concrete the joints between slabs create the conditions for interaction between slabs and steel structures. The result of this effect is that slabs take up a part of the internal forces of the steel structures and consequently diminish them in steel beams and trusses. Interaction effect was proved in a number of theoretical and experimental investigations. Some of them were carried out in Lithuania [7–9].

Interaction effect between structures may be examined in the following way.

Computational scheme (Fig 6) of roof or ceiling structures composed by reinforced concrete slabs and steel beams instead of traditionally used in such cases is substituted by the presented scheme in which slabs are Π–shaped members and steel beam – as a beam with cantilevers of the length equal to a half of the beam depth.

It should be mentioned that the rigidity problem of Π–shaped members substituting the roof slabs was examined very accurately in a great number of investigations. The ceiling slabs rigidity was determined in a rather exact way.

Quantitative changes of bending moments, as internal forces of the greatest interest in the roof and ceiling beams for various spans, have been analysed. The values of bending moments using two computational schemes were determined in two cases: in one case - taking into account the interaction effect and without it. By the way, peculiar magnitudes of roof loads for a certain time in the past were used in calculations. Ceiling structures were calculated for a load equal to 10kPa.

The calculation results are presented in Figs 7, 8.

In Fig 7 curves 1 and 3 represent the relationship between bending moments and beam span when the interaction of structures is taken into account and curves 2, 4 – the same relationship when the interaction of structures is neglected.

Analysis of the results presented in Figs 7 and 8 shows the increase of the load bearing capacity of steel beams.

4. Fire resistance of structures

Fire resistance of structures in Lithuania must be determined according to Construction Code Fire Safety, Basic Requirements [2]. The code suggests very conservative and simple solution in comparison with Eurocode 3 part 1–2 [3].

The method suggested in this paper can be useful only when using the Eurocode 3. The current Lithuanian Code does not take into account the degree of utilisation of load bearing capacity of a structure. Fire resistance of steel structures according to [2] depends only on cross-section factor:

$$t_{red} = \frac{A}{i}, \qquad (2)$$

where A and i – cross-section area and perimeter respectively. The same method of calculation is used for all structural elements types (beams, columns…).

It has already been shown above that interaction between bearing and enclosure structures can increase the load bearing capacity of structure. Possibility to use advantages of interaction between different structural elements for fire engineering calculations was discussed in [5, 6]. The possibility to use benefits of interaction between steel beam and reinforced concrete floor and roof slabs for achieving a higher critical temperature of steel beam were investigated.

Determination of critical temperatures according Eurocode was carried out for the same cases as it was performed for internal forces:

- the first case - for beam when interaction between structures is neglected;
- the second case - for beam when interaction effect with slabs is taken into account.

Critical temperature calculations were performed for the floor and ceiling beams which load bearing capacity has already been examined (Figs 7, 8). Simple calculation model was chosen for determination of critical temperature of steel beams.

Because the simple supported beams sections fit the Class 1 requirements, the design moment resistance was calculated by the formula:

$$M_{fi,\theta,Rd} = k_{y,\theta}[\gamma_{M,1}/\gamma_{M,fi}]M_{Rd}, \qquad (3)$$

where $k_{y,\theta}$ – reduction factor for yield strength of steel at temperature θ; $\gamma_{M,1}$ and $\gamma_{M,fi}$ – partial safety factors for normal and fire situation; M_{Rd} – plastic moment resistance of gross cross-section. Calculation of degree of utilisation μ_0 is based on design moment resistance for time t = 0.

Critical temperature is calculated by the formula of Eurocode:

$$\theta_{a,cr} = 39{,}19\ln\left(\frac{1}{0{,}9674\mu_0^{3{,}8333}} - 1\right) + 482. \qquad (4)$$

These calculations results are presented in Figs 9, 10.

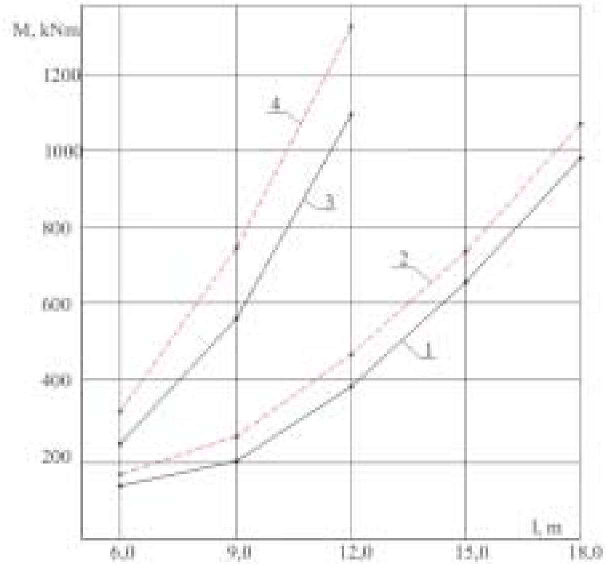

Fig 7. Bending moments of beams: 1, 2 – roof beams, 3, 4 – ceiling beams

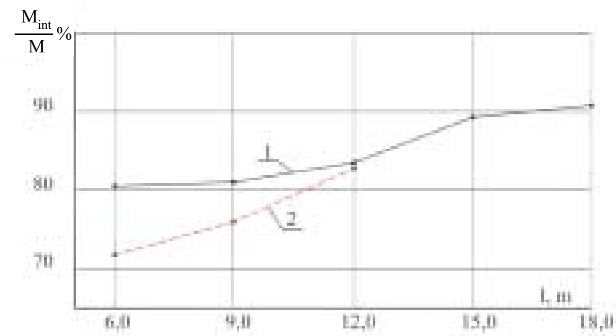

Fig 8. Relationship between beams, bending moments: M_{int} – evaluating interaction of structures, M – interaction of structures is neglected, 1 – roof beams, 2 – ceiling beams

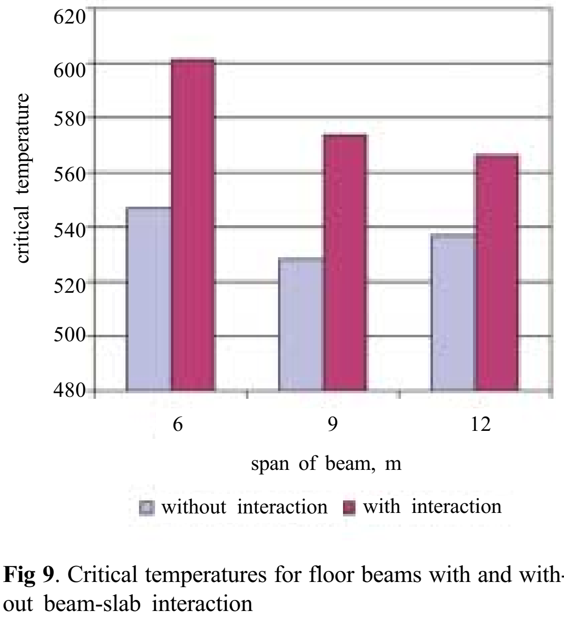

Fig 9. Critical temperatures for floor beams with and without beam-slab interaction

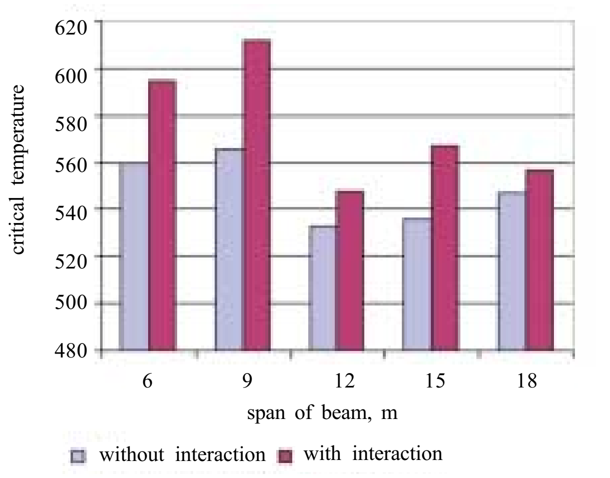

Fig 10. Critical temperatures for ceiling beams with and without beam-slab interaction

They illustrate the possibility to allow higher critical temperature for steel beams when beam-slabs interaction is taken into account. The interaction effect of critical temperature was higher for the structure composed of steel beams and ceiling slabs. Of course, it is related to character of bending moments reduction in the beams.

5. Conclusions

1. The necessary fire resistance can be achieved by using composite floor systems and composite columns elements without applying fire protection.

2. Evaluation of steel beam – concrete slabs interaction in fire engineering calculation leads to higher critical temperatures and higher fire resistance of steel beams. On the other hand, it permits to evaluate more precisely the real state of structures.

2. Formulas for critical temperature of Eurocode [3] take into account the degree of utilisation what is not included in National code of Lithuania [2]. In such a situation calculations of fire resistance for elements with a low degree of utilisation according to Eurocode is much more cost effective.

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