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Features of Evaluation of Fire Resistance of Reinforced Concrete Ribbed Slab under Combined Effect "Explosion-Fire"

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Abstract. Calculations using the example of a reinforced concrete ribbed slab have shown that if, as a result of an explosion, due to cracks that have arisen, a part of the compressed concrete layer is turned off, then even while maintaining the bearing capacity of the slab, its fire resistance is significantly reduced. It is shown that on the basis of the proposed methodology for studying the behavior of bending elements under the combined effect of "explosion-fire", it is possible to take into account the necessary parameters of reinforced concrete ribbed slabs in the design and operation of structures of hazardous operations industrial facilities. Also, the proposed technique makes it possible to predict a relatively safe amount of explosive in the technological process of an hazardous operations industrial facility, without leading to catastrophic consequences.

Introduction

At many hazardous operations industrial facilities (HIF), technological processes are carried out with substances that, under certain conditions, can explode and cause a fire. Therefore, the building structures of such facilities should be designed taking into account the danger of accidental explosions, and also correspond to the required degree of fire resistance [1, 2, 3, 4].

Industrial buildings in which HIFs are located mainly relate to the frame structural system. It can be expected that in case of explosion and fire, the consequences for supporting structures of the frame and the enclosing structures will be different [4, 5]. Even if the load-bearing bar structures, due to the low windage, can withstand such effect without significant deformations, the enclosing structures with a lower margin of safety, but selected according to the principle of compliance with the fire resistance rating, may not withstand the combined impact.

In modern frame buildings with a load-bearing steel or reinforced concrete frame, the enclosing structures are made of reinforced concrete. It is not difficult to assess the fire resistance of products made of this material.

The problem that needs to be addressed is the assessment of the effect of deformation and cracking of reinforced concrete enclosing structures as a result of an emergency explosion on their fire resistance.

Analysis of Publications

There are many publications devoted to the study of the effect of fire on reinforced concrete structures. They study experimental and computational methods for assessing the fire resistance of building structures and their technical condition, depending on the characteristics of their material and methods of organizing fire protection [6, 7].

There are also works that consider action consequences of an explosion on reinforced concrete structures. Depending on the force of the explosion, the distance of the object, the features of propagation of the blast wave, in order to predict the situation, computer modeling of the process is carried out, the magnitude and type of deformations, the places of formation and sizes of cracks are studied [8–11].

However, cases of a combination of the effects of an explosion and a fire on building structures are of particular interest.

Among recent publications, a significant place is occupied by works devoted to the protection of facilities from emergency situations (ES) associated with combined hazardous effects (CHE) involving impact (I), explosion (E), fire (F). They focus on methods for assessing the fire resistance of load-bearing structures, the dependence of the change in their critical temperature on the level of loading, and the features of ensuring the safety of people in buildings in the conditions of CHE IEF [12].

Much less attention has been devoted to the same issues regarding the enclosing structures, although from the point of view of ensuring the safety of people and preventing the spread of fire, these issues cannot be ignored [13].

In industrial buildings of HIFs, reinforced concrete ribbed slabs are often used in large quantities as enclosing structures of the built-up roof. The study of their behavior during CHE EF may be of interest both for the design of HIFs and for predicting their state after emergency situations [14].

This paper examines the combined impact of an explosion and subsequent fire on the example of a reinforced concrete ribbed slab not only from the point of view of the conditions for maintaining its stability, but also the possibility of further operation.

Statement of a Problem and its Decision

The task of the work is to assess the loss of strength, the features of cracking, the calculation of critical temperatures of reinforcement and the fire resistance limit of a reinforced concrete ribbed slab at CHE EF.

In an explosion, the action of a shock wave on the slab from below can be represented as a short-term reverse moment (SRM) causing an upward bending deformation (Fig. 1). If the slab is securely held in the attachment points, and the explosion force is insufficient to destroy it, then a tensile zone of concrete forms in the upper part of the slab. In this case, plastic deformations develop in the tensile zone of concrete and cracks are formed, the depth of which depends on the force of the shock wave. After the explosion, the slab returns to its original position, but the resulting cracks turn off a layer of concrete equal to the depth of the cracks. Thus, after the explosion, the working thickness of the slab will decrease, which will lead to a decrease in the bearing capacity and cause an increase in the reduction factor for the yield strength of a working reinforcing bar. In case of fire, this will lead to a decrease in the critical temperature of the working steel reinforcement and a decrease in the fire resistance of the slab.

Based on the above, to study the behavior of a reinforced concrete ribbed slab at CHE EF, it is necessary:

– estimate the pressure at which the plate fastening is broken (p_{br});

– check the strength of the slab under reverse bending, when the pressure of the shock wave p does not break the fastening of the slab ($p < p_{br}$);

– evaluate cracking on the upper face of the slab during reverse bending (at $p < p_{br}$) [15];

– check, under normal conditions, the strength of a slab with formed cracks on the upper face (with a reduced working slab thickness h_0);

– estimate the reduction factor for the yield strength of a working reinforcing bar γ_{st} with a reduced working thickness of slab and the critical temperature of the working reinforcement t_{cr} [16];

– estimate the fire resistance of the slab τ_{cr}.

For an example of using the proposed method, a precast reinforced concrete ribbed slab (Fig. 2) with the following parameters was chosen: the nominal dimensions of the slab are 6×1.5×0.45 m, the shelf thickness is 0.05 m, the average thickness of the longitudinal rib is 0.085 m; working conditions factor $\gamma_f = 0.9$; reliability factor in relation to the type of construction $\gamma_n = 0.95$; concrete grade B40 ($R_b = 22$ MPa); steel reinforcement of longitudinal ribs 2∅18A800 ($A_{sp} = 5.09$ cm^2; $R_s = 680$ MPa); steel reinforcement of the shelf: mesh C1 of type 4 made of wire of class A400 ∅3 with a step of 100×100 ($A_s = 0.71$ cm^2, $R_s = 365$ MPa); mesh C2 of type 4 made of wire of class A400 ∅4 with a step of 150×250 ($A_s = 0.28$ cm^2; $R_s = 365$ MPa).

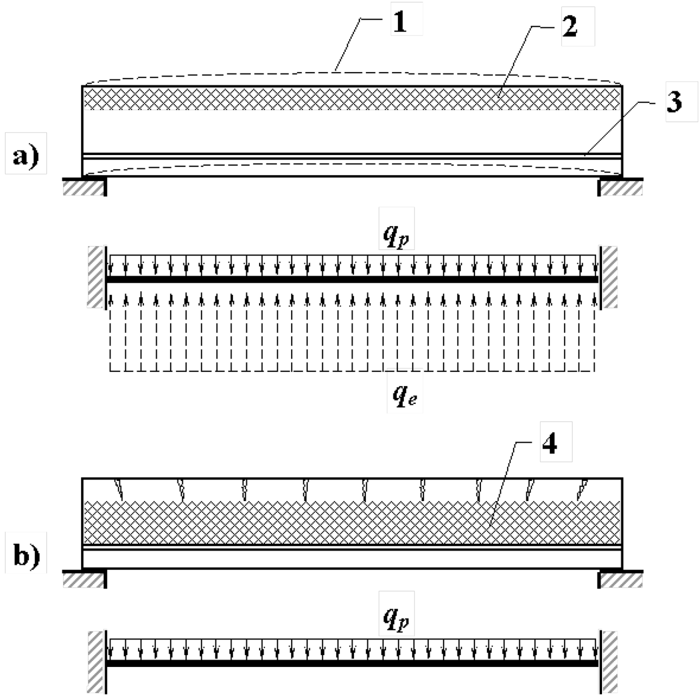

Fig. 1 Calculation scheme of reinforced concrete bending enclosing element of the roof: a) under the influence of the shock wave; b) after the impact of the shock wave. q_p – working load; $q_в$ –load from the shock wave; 1 – reverse deflection of the slab; 2 – zone of crack formation; 3 – working reinforcement; 4 – area of reduced working thickness of the reinforced concrete bending element

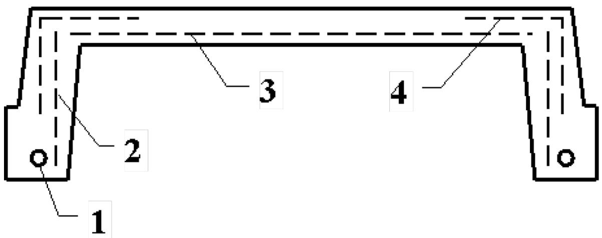

Fig. 2 Schematic diagram of reinforcement of reinforced concrete ribbed slab: 1 – working reinforcement of longitudinal ribs; 2 – planar frame of the longitudinal rib; 3 – wire-mesh reinforcement C-1; 4 – wire-mesh reinforcement C-2

The assumed uniform load on the slab is 23.2 kN/m^2, the assumed uniform load on the shelf of the slab is 21.275 kN/m^2.

The slab is welded at four extreme points along the perimeters of the embedded items with a weld length of 25.5 cm and a thickness of 1.0 cm.

Under these conditions, the tensile force of the weld will be $N_{cr} = 146000$ kN, i.e. to detach the slab, a pressure of $p_{on} = 18230$ kPa is required.

Checking the strength of the shelf of a ribbed plate for a reverse SBM is carried out taking into account the elastic edge restraint of the shelf in the longitudinal ribs and the working concrete thickness, calculated from the reinforcing mesh C1 to the lower edge of the shelf. Bearing in mind that the aspect ratio of the shelf is close to unity, we can apply the formula proposed in [17]:

$$M_n = \frac{p_{KM} b_n l_n^2}{48}, \tag{1}$$

$$\alpha_n = \frac{M_n}{b_n h_{0n\text{B}}^2 R_b}, \tag{2}$$

where M_n is the bending moment during the reverse bending of the shelf; p_{KM} is the total specific pressure on the slab during reverse bending; b_n is the clear width of the shelf between the longitudinal ribs; l_n is the clear length of the shelf between the transverse ribs; α_n is the coefficient of the working thickness of concrete of the shelf at SRM; h_{0nB} is the working concrete thickness of the shelf at SRM; R_b is the normative concrete resistance.

To calculate the strength of the longitudinal rib of the ribbed slab, its cross section is transformed to the equivalent calculated cross section as in Fig. 3.

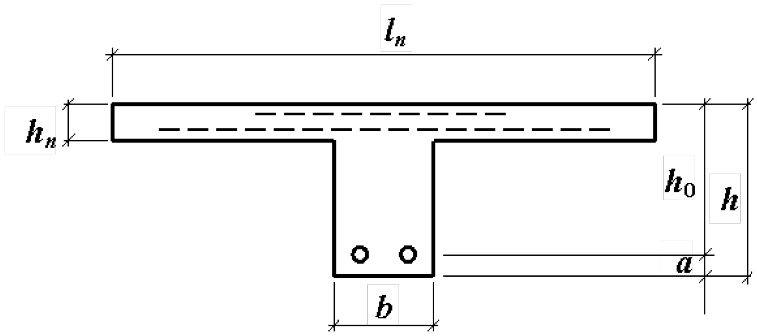

Fig. 3 Equivalent design cross section of reinforced concrete ribbed slab

Checking the strength of the longitudinal rib of a ribbed slab under the action of a SRM is carried out on the basis that the load acts on the entire slab, of which the longitudinal rib is a part, and also taking into account the hinge support on the supports and the working concrete thickness, estimated from the neutral axis to the lower edge of the rib:

$$M_p = \frac{p_{KM} b_p l^2}{8}, \tag{3}$$

$$\alpha = \frac{M_p}{b_p h_{0p\text{B}}^2 R_b}, \tag{4}$$

where M_p is the bending moment of the longitudinal rib in the middle of the span during reverse bending; b_p is the slab width along the equivalent section for the compressed zone of concrete; l is the calculated span of the slab; h_{0pB} is the effective thickness of concrete over the equivalent section at SRM.

Checking the strength of the ribbed slab in its parts shows that the shelf and longitudinal rib are destroyed when the shock wave pressure is less than the pressure that causes the weld to rupture at the attachment points. Therefore, in the future, calculations should be carried out for two cases of pressure: when the structure can withstand SRM without significant plastic deformation and when deformations of the SRM cause cracking.

The crack opening width a_{crc} is calculated according to [15]:

$$a_{crc} = l_{bs} \varphi_1 \varphi_2 \varphi_3 \psi \frac{\sigma_s}{E_s}, \tag{5}$$

where l_{bs} is the distance between adjacent normal cracks, $l_{bs} = 40$ cm; $\varphi_1 = 1$, $\varphi_2 = 1$, $\varphi_3 = 1$ are coefficients depending on the duration of the load, the type of reinforcement, the type of load; E_s is the modulus of elasticity, $E_s = 190{,}000$ MPa; σ_s is the stress in longitudinal tensile reinforcement:

$$\sigma_s = \frac{M_p}{z_s A_s}, \tag{6}$$

z_s is the distance from the center of gravity of the stretched reinforcement to the point of application of the resultant forces in the compressed zone of the element, $z_s = 33.6$ cm; A_s is the cross-sectional area of reinforcement in the tensioned zone, $A_s = 1.45$ cm^2; ψ is a coefficient that takes into account the non-uniform distribution of relative deformations of tensile reinforcement between cracks in concrete:

$$\psi = 1 - 0{,}8\frac{M_{crc}}{M_p}, \tag{7}$$

M_{crc} is the crack initiation moment:

$$M_{crc} = R_{btc} W_{pl} + M_{lm}, \tag{8}$$

R_{btc} – tensile strength of concrete corresponding to the onset of cracking, $R_{btc} = 2.1$ MPa; W_{pl} – elastoplastic moment of resistance along the stretched zone, $W_{pl} = 29845$ cm^3; M_{lm} is the core moment of the compression force, $M_{lm} = 47.8$ kN·m.

Estimating calculations according to [15] show that cracks 1 cm wide on the upper face of the longitudinal ribs of ribbed slab are formed at a pressure in the shock wave front of the order of $\Delta p = 46$ kPa. Pressure $\Delta p = 4$ kPa will be relatively safe for a ribbed slab, at which cracks of more than 1 mm do not form. For an industrial building of a hazardous industrial facility with a floor height of 9 m, the indicated pressures are achieved during the explosion of a substance with TNT equivalent of 9 kg and 0.2 kg, respectively.

It is difficult to determine the depth of the formed cracks by calculation methods. However, it can be assumed on the basis of observations [18, 19, 20] that with a cracks width of up to 1 mm, their depth will be within 1...2 cm, and with a width of 1 cm – within 10...20 cm.

Under these circumstances, the check for the ultimate limit state shows that the shelf can withstand the working load at cracks depth of no more than 2.6 cm, and the longitudinal rib – at cracks depth of no more than 4.1 cm.

Depending on the depth of crack propagation, the fire resistance of the slab will also change.

The limits of fire resistance τ of a reinforced concrete ribbed slab with cracks of various depths along the top surface of the shelf and longitudinal ribs were estimated taking into account the bearing capacity according to the method [16]:

$$erf\frac{k\sqrt{a_b} + \delta}{2\sqrt{a_b \tau}} = erf X_b = \frac{t_l - t_{crS}}{t_l - t_0}, \tag{9}$$

where k is the coefficient of concrete density; a_b is the thermal diffusivity; δ – thickness of the concrete cover; t_l is the temperature of a standard fire, $t_l = 1250$ °C; t_0 – initial temperature, $t_0 = 20$ °C; t_{crS} is the critical temperature of the reinforcement.

The determination of critical temperature of the working reinforcement t_{crS} was carried out on the basis of calculating the temperature-dependent reduction factor for local strength of steel γ_{st}:

$$\gamma_{st} = \frac{M}{R_s \cdot A_s \cdot h_0(1-0{,}5\xi)}, \tag{10}$$

where M is the bending moment from the design working load on the shelf or longitudinal rib; R_s is the standard ultimate strength of steel of reinforcement of the shelf or longitudinal rib reinforcement; h_{0c} is the working concrete thickness of the shelf or longitudinal rib along the equivalent section, taking into account the formed cracks; ξ – coefficient of the relative thickness of the compressed zone of concrete.

The results of estimated calculations of fire resistance limits of parts of a reinforced concrete ribbed slab after exposure to the shock wave are shown in tab. 1.

Tab. 1 Design fire resistance limit of a reinforced concrete ribbed slab after exposure to a shock wave, depending on the depth of cracks

Ribbed slab parts	Shock wave pressure, Δp, [kPa]	SRM, M_{KM}, [kN·m]	Crack opening width, a_{crc}, [cm]	Estimated crack depth, h_T, [cm]	Estimated fire resistance limit, τ, [min]
Shelf	0	0	0	0	40
	4	25	0.1	2.5	10
Longitudinal rib	0	0	0	0	30
	4	25	0.1	2.5	18
	10	50	0.2	4.5	10
	45	240	1.0	> 5	–

The proposed method for studying the behavior of a reinforced concrete ribbed slab at CHE EF has shown that the strength of the welded seam fastening of a ribbed slab exceeds its strength in reverse bending. Therefore, the force of an explosion that does not destroy the slab can be calculated and its parts can be examined as bending elements with appropriate fixings. Based on this, it is possible to calculate the shock wave pressure at which significant cracks will not form in the slab on the upper face and the pressure at which deep cracks appear.

According to the calculated estimate, with cracks up to 2.5 cm deep in the shelf and longitudinal ribs, the slab retains its bearing capacity, but significantly loses its fire resistance. With cracks about 5 cm deep, the slab loses its integrity (due to the shelf), but it can be assumed that this will not cause it to collapse. In this case, fire resistance can be talked about only in the sense of preventing the destruction of the damaged slab. At a crack depth of more than 5 cm, as calculations show, the slab collapses under normal conditions.

Conclusions

1. The paper proposes a method for studying the behavior of a reinforced concrete ribbed slab at CHE EF, which is also suitable for other reinforced concrete bending structures.
2. Estimating calculations showed that the shutdown of a part of the compressed concrete layer of a reinforced concrete ribbed slab, which occurred as a result of an explosion due to cracks that have arisen, has a strong effect on reducing its fire resistance. Based on these calculations, it becomes possible to take into account the necessary parameters of ribbed slabs in the design and operation of HIF structures.
3. Calculations according to the proposed methodology make it possible to justify measures to improve the safety of reinforced concrete enclosing structures of the ceiling of frame industrial buildings of hazardous industrial facilities in the event of an emergency explosion and fire. They also make it possible to predict a relatively safe amount of explosive in the HIF technological process, which does not lead to catastrophic consequences.

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