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Effect of Residual Deformation of a Steel Column on its Fire Resistance under Combined Exposure "Explosion-Fire"

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Abstract. Calculations on the example of a steel column showed that with the combined effect of an explosion that causes deformation and subsequent fire, even without damaging the fire-retardant coat, there is a significant decrease in the fire resistance of the structure due to a decrease in the critical temperature. It is shown that, on the basis of the methodology proposed in this work, for hazardous operations industrial facilities, it is possible to predict the stability of steel columns in crash explosions followed by fire, as well as to recommend the values of workloads and parameters of fire-retardant coats providing the necessary stability. It is also shown that when calculating the fire resistance limit of a steel structure with intumescent fire-retardant coat, it is necessary to take into account the proper heating time of steel structures until they lose strength.

1. Introduction

Hazardous operations industrial facilities (HIF) are designed taking into account episodic (special) impacts, reflecting the specifics of production processes [1, 2, 3]. And in the case of a production process that does not preclude an explosion, building structures are calculated on the impact of a shock wave.

On the other hand, the fire-technical characteristics of building structures of the HIF should correspond to required degree of fire resistance rating of the building. However limits of fire resistance and fire propagation on the structures without taking into account their mechanical damage are calculated.

Crash explosions in addition to damage to building structures can cause fires [4, 5]. With such a combined hazardous effect of explosion and fire (CHE EF), it should be expected that deformations of the supporting building structures during an explosion will affect their bearing capacity and, therefore, the fire resistance limit.

Since emergency explosions accompanied by fires occurring after them are highly probable at HIF, the study of the specific features of the behavior of building structures under these conditions is relevant.

A significant part of industrial buildings is steel frame construction. Therefore, it makes sense to study the behavior of precisely such constructions with CHE EF. Known works on these researches [6, 7]. However, they mainly study the causes of the degradation of structures and do not pay enough attention to the conditions for maintaining bearing capacity of structures at CHE EF.

The problem is how much the fire resistance of a steel building structure influences its deformation when exposed to a shock wave, does it need to be taken into account when checking the fire resistance rating of the building, and whether further building operation is possible after such CHE EF.

In this paper, we consider the combined effect of an explosion and a subsequent fire using the example of a steel axially-loaded column, not only in terms of the conditions for maintaining its stability, but also the possibility of further operation.

2. Study of the combined effect of "explosion-fire" on the fire resistance of steel columns

The task of the work is to calculate the critical temperatures and fire resistance limits of the steel column during deformations, which appeared as a result of impact of a shock wave, but not causing a loss of stability.

It is possible to present such column schematically in a kind of axially-loaded rod which is hinged fixed on the ends. During the explosion, the effect of a shock wave on the rod can be represented as a short-term bending moment (SBM), which causes bending deformation in the middle part of the rod [8].

With a weak impact, when only the I stage of the stress-strain state (SSS) is reached, the rod after the SBM completely restores its shape, and the fire resistance is calculated as for an axially-loaded rod.

With a stronger impact of SBM, when stage II of the SSS is reached, the residual deformation (bending) remains in the rod after the SBM. The rod in this case should be considered as compressed-bent with eccentricity e_r [9]. The stability of the rod (its bearing capacity) will depend on the parameters of the cross-section, the mechanical properties of the material and the eccentricity. In case of fire caused by an explosion, the fire resistance of the rod will be determined by the ratio of the working load N_w and the bearing capacity N_{bc}, the section parameters and the heating conditions [10].

The main danger when heating steel building structures is significant deformations and rapid loss of their strength. Therefore, during erection of buildings, various methods of fire protection are used to protect steel structures, providing the necessary fire resistance rating of the building.

However, during a crash explosion, fire protection may be damaged. It is impossible to guarantee the safety or damage of fire protection during an explosion. Therefore, it is advisable to evaluate the fire resistance of steel structures not by fire resistance limit, but by their critical temperature.

For the axially-loaded steel column, according to the methods recommended in [9, 10], it is possible to find the value of the buckling coefficient φ and determine the critical temperature under the working load N_w, by calculating the bearing capacity reduction factor γ_T:

$$\gamma_T = \frac{N_P}{\varphi A_K R_S} , \tag{1}$$

where A_K – cross-sectional area of the column; R_S – ultimate strength of steel.

After deformation of the column as a result of explosion, when it is considered as a compressed-bent rod with eccentricity of e_r, it is possible by [9] to calculate the conditional flexibility λ_e:

$$\lambda_e = \frac{H}{r}\sqrt{\frac{R_s}{E}} , \tag{2}$$

where H – height of the column; E – modulus of elasticity of steel; r – radius of inertia.

Further, for different values of eccentricity, e_r calculates the values of reduced eccentricities μ:

$$\mu = \eta e_{ocm} \frac{A_K}{W} , \tag{3}$$

where η – section shape factor; W – modulus of section. The radius of inertia and the modulus of section should be chosen relative to the “weak” axis, which provides maximum flexibility.

Then, according to [9], it is possible to find the stress reduction factors with an eccentric columnar deflection φ_B. Substituting these values into (1) and calculating the bearing capacity reduction factors γ_T, one can determine the critical temperatures for various values of eccentricities e_r by [10].

As an example of steel construction, single-support axially-loaded steel columns of various profiles, heated in case of fire from 4 sides, are considered. For calculations, steel columns with the height H = 8 m of such profiles were selected: wide-flanged H-beam, bent welded pipe of square section, welded pipe of circular cross section. Parameters of the columns were chosen to be comparable in terms of flexibility, cross-sectional area and radius of inertia. Calculations were carried out for columns made of steel with an ultimate strength R_S = 21 kN·cm^{-2} and an elastic modulus of E = 21000 kN·cm^{-2}. The results of the calculations are given in Table 1.

Data analysis Table 1 shows that during an explosion, the deformation of an 8-meter steel column, which does not cause a loss of bearing capacity, nevertheless leads to a decrease in its critical temperature by 150–200 °C. When the load factor of the column is less than K_z = 1.8, a deflection of 4–6 cm leads to a decrease in the critical temperature to 150–200 °C. According to the results of calculations, the fire resistance limit of an unprotected steel column is not more than R15, which does not correspond to the required fire resistance rating of building.

3. Analysis of the Effectiveness of the Flame-Retardant Coat of a Steel Column at CHE EF

Flame-retardant coats are used to protect steel structures from fire. Typically, such coats are calculated on the steel structure reaching a critical temperature of 450–500 ºC. Intumescent coats show the best adhesion to steel. Therefore, they should be used for fire protection of steel structures with the probability of crush explosions [11].

Intumescent coats begin to work with a temperature of 150–220 °C [12]. Table 1 shows that at such temperatures, after impact of the shock wave, the column may already be on the verge of loss of bearing capacity. That is, the deformation of a steel column at explosion even without damage of a flame-retardant coat will lead to a significant reduction in its resistance to fire.

On the other hand, it is clear from the Table 1 that at the design stage of a HIF, it is possible to calculate the working load on a structure, for which under condition of retain of a flame-retardant coat at explosion necessary stability will be provided.

Existing calculation methods allow to count efficiency of intumescent coats authentically. They consider time of warming up of an initial layer prior to the beginning of it intumescent and, then, time during which the intumescent layer is capable to protect a structure [12, 13]. For steel structures in connection with high heat conductivity of metal the time of achievement of fire resistance limit consider the moment when temperature on border "covering – metal" becomes to equal critical temperature of a structure [12]. Values of fire resistance limits, calculated thus, do not consider time of warming up of actually metal structure which is in a stress state. Therefore they can be a little underestimated. It can lead to the over-expenditure of materials or the inexact forecast of steel structures behavior at a fire.

It is possible to present a fire resistance limit of a steel structure τ_{kp} as the sum of warming up times:

τ_{Fb} – of a protective coat to its temperature of intumescent t_{Fb};
τ_{Fs} – of a intumescent layer to critical temperature of a steel structure t_{kS};
τ_{kS} – of a steel structure before loss of strength by it:

$$\tau_{kp} = \tau_{Fb} + \tau_{Fs} + \tau_{kS} \,. \tag{4}$$

According to the method [14], calculations were made of the fire resistance limits of selected steel columns covered with a “Terma” intumescent composition with characteristics: an intumescent coat density ρ = 0.8 kg/m^3; effective factor of heat conductivity λ_{ef} = 0.05…0.32 W/(m·K); intumescent factor k_{sw} = 15; critical value of intumescent temperature t_{Fb} = 177 °C, initial coating thickness δ = 1 mm. The results of these calculations are shown in Table 1.

Table 1. Estimated values of the fire resistance of single-support steel columns covered with "Terma" fire-retardant intumescent composition

Column profile	Column workload, N_p, [kN]	Eccentricity, e_{ocm}, [cm]	Reduction factor of load carrying capacity, γ_T	Critical temperature of the column, t_{kp}, [°C]	Warm-up time of the column to t_{kS}, τ_{kS}, [min]	Warm-up time of coat to t_{kS}, τ_{kS}, [min]	Fire resistance, τ_{kp}, [min]
Column Pipe 200×200×6; A = 58,7 cm^2; r = 7,73 cm; W = 351 cm^3; $\delta_л$ = 0,734 cm	400	0	0,579	500	9	28	35
		1	0,60	485	8	27	34
		2	0,67	430	7	21	26
		4	0,76	310	5	13	16
		6	0,92	156	3	–	–
Column Pipe ∅ 273×7; A = 58,5 cm^2; r_x = 9,42 cm; W_x = 593,5 cm^3; $\delta_л$ = 0,682 cm	400	0	0,454	600	13	42	51
		1	0,458	596	13	42	50
		2	0,471	591	12	41	49
		4	0,508	577	12	38	45
		6	0.581	500	9	28	33
		8	0,664	463	7	25	30
		10	0,723	406	6	19	22
	700	0	0,798	320	5	14	16
		1	0,796	317	5	13	15
		2	0,825	281	4	11	13
		4	0,890	225	3	7	9
Column H-beam 484×300×11×15; A = 122,4 cm^2; r_y = 7,18 cm; W_y = 420 cm^3; $\delta_л$ = 0,625 cm	400	0	0,303	634	15	48	59
		1	0,305	632	15	47	58
		2	0,344	598	14	42	52
		4	0,418	585	13	40	49
		6	0,486	536	11	33	40
		8	0,555	509	10	29	35
		10	0,622	470	8	25	31
	700	0	0,531	530	11	32	38
		1	0,530	529	10	31	37
		2	0,605	467	8	25	30
		4	0,736	395	7	19	23
		6	0,851	195	4	5	7
		8	0,970	133	3	–	–

The resulted example shows that at estimation of fire resistance of steel structures protected by a intumescent coat "Terma", the time of warming up of actually steel structure before they will lose strength, makes 10…16 % from a settlement limit of fire resistance. And this contribution will increase at increase in the resulted thickness of a structure. It should also be noted that since the critical temperature of steel structures depends on the magnitude of working load on them and ultimate strength of steel, these criteria should be taken into account when designing fire protection [15].

4. Conclusion

Thus, on an example influence of residual deformation of a steel column after crush explosion on its fire resistance is shown. Deformation of a column during an explosion leads to decrease in its bearing capacity and, consequently, to decrease in critical temperature and fire resistance limit.

When a column is deformed, the effectiveness of flame-retardant coats decreases, since even without their damage, a fire resistance of a structure is reduced. The situation when because of column deformation its critical temperature becomes lower than intumescent temperature of a flame-retardant coat is possible.

Thus, it is shown on an example that at calculations of fire resistance limit of steel structure protected by intumescent coat, it is necessary to consider in addition to the heating time of the intumescent coat to critical temperature, also time of loss of strength of the steel column itself, which depends on workload on it, ultimate strength of steel, thermal diffusivity of steel and the reduced column thickness.

Based on the methodology considered in this work for hazardous operations industrial facilities, it is possible to predict the stability of steel columns in crush explosions with subsequent fire, and also to recommend the values of workloads and parameters of flame-retardant coats that provide the necessary stability.

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