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Experimental and theoretical study of reinforced concrete elements under different characteristics of loading at high temperatures

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Abstract

In this article we have represented the results of dynamic calculation of eccentrically loaded reinforced column strength under different temperatures, which show, that the dynamic strength of the column is greatly reduced compared to the static strength. Transition from one working stage of element to another under dynamic loading occurs faster. Using the developed method we have shown the results of dynamic calculation of eccentric compressed reinforced concrete column at different high temperatures under different characteristics of loading, taking into account the experimental studies.
The following article also presents the results of nonlinear dynamic calculation of reinforced concrete multi-story frame at different temperatures, which are counted taking into consideration the changes of values of plastic hinges depending on temperatures.

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Keywords: Reinforced concrete column, high temperatures, dynamic loadings, coefficient of dynamic strength, eccentricity

1. Introduction

Analysis of research devoted to the study of reinforced concrete elements operating at high temperatures shows, that the study of strength and deformability of such elements was carried out, for the most part, under static loading [1-3], but as practice shows, in many cases, in emergency situations load combination influence on structural elements of buildings takes place [4,5]. Data of the reduction dynamic characteristics of reinforced concrete

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elements exposed to fire and after cooling are practically absent; however, they are necessary in the calculation of the frame of the building under non-project impacts.

Dynamic loading on the structure may be different depending on the character of its time dependence.

2. Experimental studies

For experimental researching and development of calculation methods of strength and deformability of reinforced concrete elements under dynamic loading at high temperatures, 2 types of dynamic loadings were taken, depending on time varying according to the following laws:

- Power function; $$N(t) = \frac{N}{1 - t/t_{ef}} \text{ at } 0 \prec t \prec t_{ef} \quad (1)$$

- Exponential function; $$N(t) = N_m e^{-\frac{1}{E}\left(\frac{t - t_{ef1}}{B}\right)^2} \quad (2)$$

Dynamic loading was studied at 4 loading rates; 0.07s, 0.1s, 0.4s, and 1.0s.

Concrete and reinforced concrete elements were heated up to 300 ° C, 500 ° C, 700 ° C and 900 °C according to the standard temperature regime $(T = 345\lg(8\tau + 1) + t_e)$.

For studying the dynamic strength of the compressed and compressed-bent reinforced concrete elements at high temperatures, reinforced concrete columns with dimensions $100x100x600\,mm$ with relative eccentricity $(e_0 / h = 0{,}3;0{,}35;0{,}4)$ were tested.

It was proved, that the coefficient of dynamic strength of concrete, depending on the heating temperature, decreases up to 0.47. The dependence of the dynamic strength coefficient on different temperatures and also on the dynamic loading rates is presented in the Table 1.

Table 1. The values of coefficient of dynamic strength Concrete $K_{d,bT}$ at loading rates t = 1,0 s and t = 0,4 s depending on temperatures

T (˚C)	Concrete cubes($K_{d,bT}$)		Concrete prisms($K_{d,bT}$)	
	t=1,0s	t=0,4s	t=1,0s	t=0,4s
20	1,188	1,218	1,190	1,194
300	0,960	0,959	0,961	0,957
500	0,844	0,841	0,843	0,831
700	0,590	0,585	0,596	0,585
900	0,470	0,441	0,490	0,460

Cube and prism strength of concrete under static loadings was reduced to 87.94% (at 900 ° C). Dynamic tests for determination of cube and prism strength of concrete at loading time t=1,0s showed, that dynamic strength decreases by 95,23 % (at 900°C), and by 96,2% at loading time t=0,4s.

Analysis of the residual strength of the reinforcing steel class of A500 after heating showed the following results: in normal conditions, breaking strength equals 34,70 kN, after heating to 900°C it was reduced up to 30,1 kN, i.e. the residual strength of the reinforcing steel was 86,0%.

After heating up to 600°C, elasticity modulus of reinforcement steel was fully restored. In this case, the change of static strength characteristics rebar has been revealed. Reduction of reinforcement steel elasticity modulus after heating to 900°C composed 13,86%.

Experimental studies of compressed concrete elements were carried out with 2-speeds of dynamic loading: at 0.4s and 1.0s under central compression and various eccentricities [6,7]: $e_0 / h = 0{,}3;0{,}35;0{,}4$.

Studies showed, that under static loading the decrease of the strength of centrally compressed reinforced concrete columns at 900˚C temperature reached to 52.76%, while for eccentrically compressed reinforced concrete columns it reached to 64,19 %. Dynamic strength of centrally compressed reinforced concrete columns was reduced: at the loading time t=1,0s by 59,09%, at t=0,4s – 65,80%. Dynamic strength of eccentrically compressed reinforced concrete columns was reduced to 83,14% (e=4,0cm).

3. Development of calculation methods

On the basis of experimental data, we developed a method of dynamic calculation of reinforced concrete elements taking into account the temperature. The developed program is based on values of the plastic hinges on reinforced concrete elements, and, as shown by the majority of studies, it allows in the best way to characterize the work of calculated elements in 3 stages of deformation.

Dynamic calculation accounting the temperature begins from thermo-technical calculation.

The temperature at the calculating point of rebar is defined by the formula:

$$t_{x(арм)\tau}=1250-(1250-T_0)\left(Erf\left[\frac{\zeta}{2\sqrt{F_0}}\right]+Erf\left[\frac{2-\zeta}{2\sqrt{F_0}}\right]-1\right) \tag{3}$$

Previously, the section of column is divided into 5 parts, and the temperatures in the middle of each part are defined. The temperature in the middle of the parts is determined by the formula

$$\zeta(n)=1-\frac{(5-n)\cdot b/10+b/20}{0{,}5b+K\sqrt{\alpha_{red}}}. \tag{4}$$

After determination of the required temperature in the section of column, dynamic calculation is divided into 2 parts.

At a temperature of reinforcement steel t <100ºC calculation is made using existing methods, however, when t ≥100ºC the calculation is made taking into account the changes of the strength and deformation characteristics of materials depending on temperature.

The equation of motion of the work of reinforced concrete columns under dynamic loading is considered in 2 stages.

Column movement in the elastic stage represents a differential equation of 4th degree, where the deflection includes static and dynamic deflections

$$B_1(T)\frac{\partial^4 y_1}{\partial z^4}+N(t)\frac{\partial^2 y_1}{\partial z^2}+m\frac{\partial^2 y_1}{\partial t^2}=0. \tag{5}$$

Stiffness of element, which is a part of motion column in equation, is determined depending on temperature; also we determine natural oscillation frequency of element at this stage, according to the methods described in the works [8-10].

For transition to second stage of work of element, i.e. to elasto-plastic, it is necessary to know the time of formation cracks, which is determined by the formula:

$$(t_1(T)-t_{eff1})^2+E(T)B(T)^2\ln[C(T)+13{,}5Exp(-\frac{t_{eff1}{}^2}{E(T)B(T)^2})\cos\omega_1 t_1(T)]=0. \tag{6}$$

The end of elasto-plastic stage, i.e. the beginning of plastic stage of work of element is defined by formula:

$$(t_2(T)-t_{eff1})^2=-E(T)B(T)^2\ln\left\{K-B_{2d}(T)\frac{\pi^2}{l^2}\left[C_n(T)\sin\omega_{n2}(t_2(T)-t_1(T))+D_n(T)\cos\omega_{n2}(t_2(T)-t_1(T))\right]\right\}. \tag{7}$$

Unlike the equations of column`s motion in elastic stage, motion in plastic stage depends on value of plastic hinges:

$$\varphi(t)-\lambda^2\varphi(t)=-M_{uo}\frac{24}{ml^3}. \tag{8}$$

After determination of the value of the maximum angle of the plastic hinge and comparison with the ultimate value, it is necessary to check the strength criteria.

Criteria of strength of column at formation therein n plastic hinges take the form:

$$\psi_i \le \psi_{i.u} \text{(i=1,2,3,…n).} \tag{9}$$

Here ψ_i and $\psi_{i.u}$ - are angles of plastic hinge in i-th joint plasticity.

If $\psi_{max}(T) \succ \psi_u$, the element is destroyed.

4. Results

As an example, we present the dynamic calculation of eccentrically compressed reinforced concrete columns at different temperatures of fire by using developed programs [7].

Initial data: section $100\times100mm$; effective length $L_0 = 600mm$.; class of concrete B30, average density in a dry condition (granite crushed stone) $\rho_{av} = 2485kg/m^3$, gravimetric humidity $w = 4{,}6\%$, reinforcement 4Ø8 A500, depth of concrete cover $a_0 = 12mm$.

The results of calculation are shown with the column at a relative eccentricity $e_0/h = 0{,}35$ in normal conditions and in standard high temperature regime at 320s and 1 000s, respectively, $T = 500^0C$ and $T = 900^0C$, under maximum dynamic loading equal to Nm=71kN.

The calculation allows to construct diagram of 'moment – curvature' compressed reinforced concrete element, working under normal conditions and at high temperatures (fig. 1a), and to build a graph of changes of the static and dynamic strength column (fig. 1b) depending on temperatures.

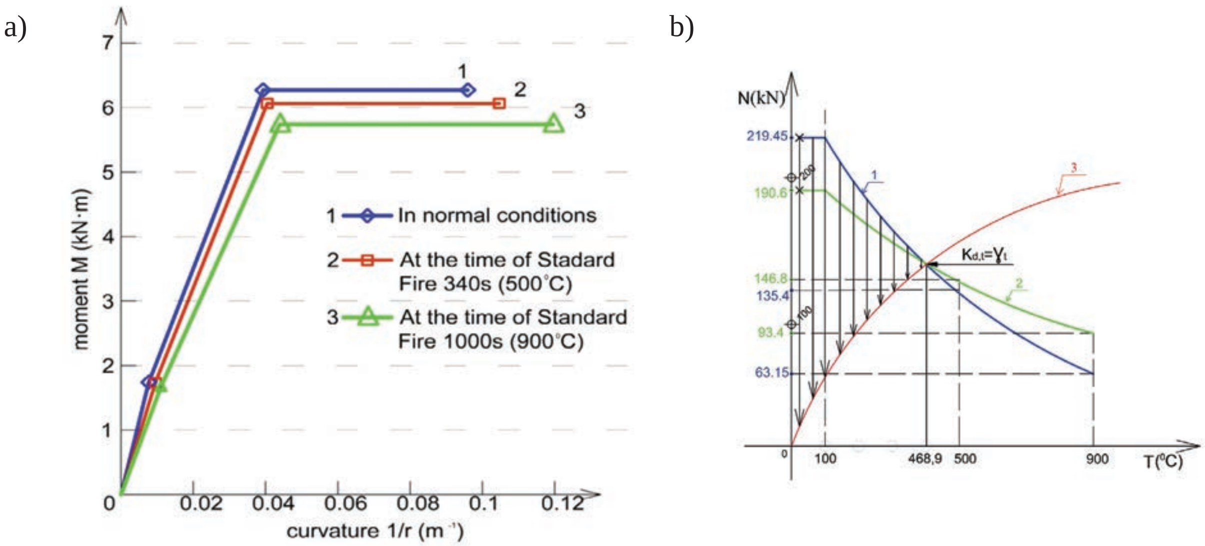

Fig 1. Diagram of depending 'moment – curvature' eccentrically compressed reinforced concrete element (a); Diagram of changing (b);

1 - Dynamic; 2 - Static strength concrete columns under standard temperature regime; 3 - fire temperature according to ISO 834

The calculation results show, that the formation of the first cracks in the conditions of fire exposure occurs at $T = 500^0C$ and $T = 900^0C$ - 1.3 times and 3.4 times faster than in normal conditions, respectively. In normal conditions stiffness of elements in the stage without cracks is 1,16 times greater than at the temperature $T = 500^0C$, and 1,45 times greater than at $T = 900^0C$.

During the calculation of the frame multistory building for the progressive collapse by nonlinear static load calculations we define the load, acting on the column of the first floor, which equals to 7003 kN. After definition of the mode of vertical wavering of structure, from which we determine the dynamic load application speed, we make this load from the bottom-up and carry out a non-linear dynamic analysis of buildings at the temperatures $20, 500, 900^0 C$ by using program complex Sap 2000 v 12.

The maximum value of plastic hinges ($\psi_{\max T}$) determines the stage of deformation of the "key" elements, which is in Life safety stage at T=$20^0 C$ and T=$500^0 C$ temperatures.

Plastic hinges after the non-linear dynamic analysis of structure at T=$900^0 C$ show that column is destroyed (stage E), in this case the destruction of column is fixed under load equal to P =5178кН.

Analytical calculation and numerical analysis of column of 25-story reinforced concrete frame of the building show, that the frame resistance to progressive collapse, when the fire temperature is T=$900^0 C$, is not provided, as evidenced by the presence of unacceptable deformations in plastic hinges on the bearing elements of the building - Stage E. Thus, the calculation of the building at different thermopower influences by using plastic hinges with considerable changes of the static and dynamic strength properties of the constituent materials, allows to precisely assess the resistance of buildings to progressive collapse.

5. Conclusion

1. Dynamic strength of centrally compressed reinforced concrete columns under high temperatures is reduced by 66.0%, and the eccentrically-compressed reinforced concrete columns by 83.2%.
2. The stiffness of the compressed concrete elements without cracking is 1.16 times greater than at the temperature $T = 500^0 C$, and 1.45 times more than the stiffening of element in stage I at $T = 900^0 C$. At the high temperatures, the time of transition from elastic to elasto-plastic stage is 1.32 times less than after cooling.
3. In this case of calculation, the value of plastic hinge of the reinforced concrete column after cooling is 00210 ($T = 500^0 C$), which is 1.35 times smaller than under high temperature, respectively, the deflection at the high temperature is 1.69 times more than after cooling.
4. Nonlinear dynamic analysis of the structure at different temperatures carries out the different stages of work of the plastic hinges.

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