Equivalent viscous damping ratio for a RC column under seismic load after a fire

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Abstract. The problem of taking into account combinations of special influences in the design of buildings and structures is currently quite relevant. In the event of a combination of fire and seismic load, two options are possible: fire after an earthquake and an earthquake after a fire. This work is devoted to the development of the methodology for calculating RC columns when the second option appears. It is known that fire effects reduce the mechanical characteristics of concrete and reinforcement. When calculating for seismic loads, it is also important to understand how the properties of a structure change during heating to dissipate deformation energy under low-cycle loads. When calculating RC columns using the displacement based design (DBD) method, dissipative properties are estimated the viscous damping ratio. In this work, this ratio is determined by considering the energy losses in one cycle of oscillations, which are equal to the area of the hysteresis loop. Hysteresis loops are determined by numerical calculation of RC columns for a combination of vertical preload and quasistatic horizontal displacement. The mechanical properties of the columns correspond to different fire times: 0, 30, 60, 90 and 120 minutes. In numerical modeling, it was found that the total energy that the column is capable of dissipating decreases with increasing duration of fire exposure. In its turn the hysteresis damping ratio at different fire duration can be either more or less than its initial value. The hysteresis damping coefficient decreases only for a time of fire of 30 and 60 min. With a longer fire duration (90 and 120 min), the coefficient does not decrease.

1. Introduction
There are two possible scenarios of the combination of fire and seismic effects in the design of RC structures. Namely fire after an earthquake and an earthquake after a fire.

The first option is more common in practice, and therefore more studied [1-4]. There are cases when the collapse of structures did not occur as a result of an earthquake, but as a result of the subsequent impact of a fire caused by an earthquake.

Research in this direction is mainly associated with the determination of damage that occurs in a RC element after seismic load. For example, such an indicator of damage can be the opening angle of plastic hinges [1]. Further, the degradation of the resistance of RC structures to fire impact is assessed, which is quantitatively measured in reducing the limit of fire resistance.

A few works [5-7] are devoted to the consideration of the second option, when an earthquake occurs after a fire. It can be associated with the occurrence of repeated earthquakes (aftershocks), when the main shock is the cause of the fire, and after some time of the fire, a second shock occurs.
In addition, the need to determine the seismic resistance of a structure after exposure to a fire may arise when assessing the need to strengthen it in the event of the danger of a subsequent possible earthquake.

Thus, the development of methods for determining the seismic resistance of columns after exposure to fire is an urgent problem. Calculations are impossible without determining the key characteristics of the system corresponding to this calculation methodology, which are used as input data and are considered known.

These key characteristics are usually determined experimentally, including on the basis of numerical modeling. In the case of seismic loading after a fire, it is important to determine not only the parameters that determine the stress-strain relation in the case of dynamic loading, for example, when assessing the resistance of a structure to progressive collapse after a fire \[8-9\]. It is also important to specify the dissipative properties of the system under the action of low-cycle loading.

One of the advanced methods for calculating RC structures for seismic loads is the method displacement based design (DBD) [10].

Without describing the algorithm of the DBD method, we only note that the main characteristic in determining the seismic response of a system is the viscous damping ratio $\xi_{eq}$, which is the ability of the structure to dissipate deformation energy.

The viscous damping ratio is the sum of two parameters: the elastic damping ratio and the hysteresis damping ratio.

$$\xi_{eq} = \xi_{el} + \xi_{hyst}$$ (1)

Usually for RC structures $\xi_{el} = 0.05$.

The hysteresis damping ratio $\xi_{hyst}$ is determined experimentally for each construction. It is proportional to the ratio of the energy dissipated in one cycle of oscillations $E_d$, which is equal to the area of the hysteresis loop, to the potential strain energy $E_s$ (Figure 1) [11].

$$\xi_{hyst} = \frac{E_d}{2\pi E_s}$$ (2)
The purpose of this paper is to determine the damping properties of a RC column with different time of fire. These properties will be estimated using the hysteresis damping ratio $\xi_{hyst}$.

This kind of research was carried out in [11, 12]. RC structures were tested under low-cycle loads. As a result of the analysis of the hysteresis loops, dependences were proposed for determining the viscous damping ratio.

There are similar studies of reinforced concrete columns previously exposed to fire [5]. It has been found that increasing the duration of the fire decreases the energy dissipation capacity of the columns. However, no relation has been proposed between the damping properties and the time of fire.

2. Methods

The paper investigates the ability to dissipate the energy of the central column of the RC frame at different time of fire.

Under conditions of seismic load, the floors receive displacements in the horizontal direction of different magnitude. The columns in these conditions work as shear links, preventing the mutual displacement of the floors (Figure 2).

The column in these conditions can be imagined as a rack with rigid fixings at both ends, one of which is movable in the horizontal direction. The column is subjected to a static axial preload and seismic horizontal action at the level of the upper termination. Seismic load can be represented as a horizontal displacement equal to the mutual displacement of one floor relative to another (rigid loading).

To reduce computational costs, we will use the well-known technique [13], when a column can be represented as a console half a floor high (Figure 3). In this case, the calculated horizontal displacement will be half the mutual displacement of the floors.

The dissipative properties of a reinforced concrete column will be mainly caused by the specifics of concrete operation under low-cycle loading. It is known that under conditions of low-cycle loading, the behavior of concrete depends significantly on the level of initial stresses [14]. Therefore, when carrying out numerical simulation, the vertical load was selected from the condition of ensuring the same stress level in concrete for all tested columns. The axial load ratio $\nu$ was taken to be 0.5.
Figure 3. To justify the design scheme.

\[ \nu = \frac{V}{A_c f_{cm}} \]  

where \( V \) – axial load;

\( A_c \) – average cross-sectional compressive strength of concrete;

\( f_{cm} \) – area of the column cross section.

To determine the hysteresis damping ratio \( \xi_{hyst} \) for column used by the pushover-analysis [15]. The horizontal displacement represented as quasi-static. Then all plastic deformations and the viscous damping energy of the column, will be realized in the first loading cycle.

The displacement of the upper end of the half-column is taken as a seismic type load. The largest displacement amplitude at the level of the middle of the column for all samples was taken to be the same and equal to 10 mm, which corresponds to a mutual displacement of the floors of 20 mm.

The bearing capacity curve in the horizontal displacement-horizontal force axes \( (\Delta - H) \) was approximated by a bilinear diagram (Figure 1). The approximation was carried out proceeding from the condition of equality of the areas \( A_1 = A_2 \).

For the sake of simplicity, the conversion of the bearing capacity curve to the acceleration-displacement response spectra (ADRS) is not done. Obviously, the value of the equivalent viscous damping ratio \( \xi_{eq} \) calculated from these two diagrams will be the same.

The energy dissipated \( E_d \) and potential strain energy \( E_s \) is calculated by the formulas

\[ E_d = 4(H_{el} \Delta_{pl} - \Delta_{el} H_{pl}) \]  

\[ E_s = \frac{H_{pl} \Delta_{pl}}{2} \]

where \( H_{el}, \Delta_{el}, H_{pl}, \Delta_{pl} \) – the physical meaning of the quantities is explained in Figure 1.

The hysteresis damping ratio \( \xi_{hyst} \) is calculated by the formula (2).

In numerical modeling, 5 columns are considered. The properties of concrete and reinforcement are taken depending on the temperature in a given finite element. The distribution of the temperature field over the cross section of the samples was taken on the basis of the data of the thermal engineering
calculation, which is given in standard STO 36554501-006-2006 «Fire Resistance and Fire Safety of Reinforced Concrete Structures» for columns exposed to fire from four sides.

The column will be considered equally heated in height. When taking into account the uneven distribution of the thermal field, one should take into account the stochastic nature of the fire effect and calculate the structure using the methods of reliability theory.

Temperature fields along the column cross-section are taken depending on the time of fire $\tau$, which takes values of 30, 60, 90 and 120 minutes. The modeling of a RC column was also carried out, which was not exposed to fire.

The variable characteristics for concrete are the design axial compression strength $f_c$, the initial elastic modulus $E_c$, and ultimate relative plastic deformations $K_{pl}$. The latter are defined as the difference between the total relative deformations and their elastic part.

$$K_{pl} = \varepsilon_{tot} - \varepsilon_{el}$$  \hspace{1cm} (6)

For reinforcement, the variable characteristics are the design axial tensile (compression) strength $f_s$ and the elastic modulus $E_s$.

The samples are 1500 mm high (floor height 3000 mm). The cross section has dimensions of 400x400 mm and is reinforced with four rods of Ø20 mm, the class of reinforcing steel is A400. The columns are made of B25 class concrete. The concrete work is described using the Drucker-Prager’s model.

3. Results

In figure 4 shows the deformed state of the half-column with the horizontal deviation.

In figure 5 shows the bearing capacity curve for column after a fire of varying duration. The diagram is given in two versions: based on the results of numerical calculation and its bilinear approximation. The magnitude of the horizontal force was defined as the reaction that occurs in the embedment.

With an increase in the duration of the fire, the stiffness of the columns in the horizontal direction decreases significantly. This leads to a decrease in the width of the hysteresis loops and an increase in their slope to the deformation axis. In this way with an increase in the duration of the fire effect, the ability of the columns to dissipate deformation energy decreases.

![Figure 4. RC column in a deformed state and the value of horizontal displacements](image.png)
Figure 5. The bearing capacity curve for column after a fire.
Figure 6. Diagram of the change in the hysteresis damping ratio depending on the displacement ductility factor for different duration of fire.

In its turn the hysteresis damping coefficient decreases only for a time of fire of 30 and 60 min (Figure 6). With a longer fire duration (90 and 120 min), the coefficient does not decrease, and at \( \tau = 90 \) min, even slightly more than for a column that is not exposed to fire. This is due to the fact that the work done on the column is also reduced.

Where \( \mu \) is the displacement ductility factor equal to the ratio of total horizontal deformations \( \Delta_{pl} \) to their elastic part \( \Delta_{el} \).

\[
\mu = \frac{\Delta_{pl}}{\Delta_{el}}
\]  

The figure 7 shows a comparison of the change in relative dissipative energy \( \frac{E_d}{E_{do}} \) and the hysteresis damping ratio \( \xi_{hyst} \) versus the time of fire at a displacement ductility factor of \( \mu = 2.5 \). It can be seen that the coefficient \( \xi_{hyst} \), in contrast to the relative dissipated energy \( \frac{E_d}{E_{do}} \), with an increase in the duration of the fire, can be either greater or less than the corresponding value in the absence of fire.

4. Conclusions
1) Based on the results of numerical modeling, it was found that the total energy that the column is capable of dissipating decreases with increasing time of fire. The width of the hysteresis loops and relative dissipative energy decreases with increasing fire duration.

2) The hysteresis damping ratio \( \xi_{hyst} \) at different fire duration can be either more or less than its initial value (at \( \tau = 0 \) min). Thus, the seismic response of the column depends significantly on the time of fire, which must be taken into account when designing.
**Figure 7.** Diagram of the dependence of the relative dissipative energy (a) and the hysteresis damping ratio (b) on the time of fire ($\mu = 2.5$).
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