Model Analysis for Identifying the Load-Bearing Capacity and Fire Resistance of the Reinforced Concrete Column

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Abstract. In this paper a new technical solution in construction industry is presented, that relates in particular to testing compressed reinforced concrete elements - the building’s columns - for strength, stability and fire resistance, using scaled models. The subject matter is increasing the informative value, visual clarity and depth of experimental research of columns, using an economical technique of designing the geometric and force similarity of the reinforced concrete column’s scaled model for analyzing load-bearing capacity: strength, stability and fire resistance. The technical result is to identify the reinforced concrete column’s actual operation and its stress state from the beginning of the test and up to the stage of destruction; to evaluate the reinforced concrete column’s limit state according to its load-bearing capacity and fire resistance; to develop the analytical model for calculating the actual fire resistance limit; to save the labor costs for manufacturing the scaled test model of the real structure.

1. Introduction
The technical solution described in this paper relates to construction industry, in particular, to testing compressed reinforced concrete elements - the building’s columns - for strength, stability and fire resistance, using scaled models.

2. Materials and methods
The technical solution relates to construction industry, in particular, to testing compressed reinforced concrete elements - the building’s columns - for strength, stability and fire resistance, using scaled models.

There is a well-known method of identifying the load-bearing capacity of reinforced concrete structures, which uses scaled models for identifying the structures’ actual operation and stress state at different stages of construction and operation up to the stage of destruction [1]. However, this method describes only the general principles of building structures’ simulation and the peculiar features of scaled models’ tests. The essence of the technical solution proposed by the authors is increasing the informative value, visual clarity and depth of experimental research of columns, using an economical technique of designing the geometric and force similarity - the reinforced concrete column’s scaled model for analyzing load-bearing capacity and fire resistance.

Designing and manufacturing the scaled model with a given similarity constant, identifying the geometric characteristics of the model and of the real structure, as well as the strength characteristics
of concrete and reinforcement, determining the simulation efforts required to identify the column’s load-bearing capacity and fire resistance, evaluating the thermal diffusion indicators of concrete, identifying the strength of the model’s and the real structure’s design section under normal operating conditions, calculating the failure moment value under fire test conditions in the model’s and the real structure’s section, identifying the duration of the model’s resistance to fire test and the value of the real column’s fire resistance limit as a load-bearing capacity criterion.

The dimensionally scaled model as related to the real reinforced concrete column is described by the equations (1):

\[ b_m = b \cdot m; \quad h_m = h \cdot m; \quad h_{o,m} = h_o \cdot m; \quad a_m = a \cdot m; \]

where \( b, h, h_o, a \) – are the width, depth, effective depth of the column’s section and the laying depth of reinforcement accordingly, \( mm \); \( m \) is the model’s similarity constant.

Adherence to the strength indices of the model’s reinforcement and concrete are described by the equations (2 and 3):

\[ A_{s,m} = A_{s,m} = A_s \cdot m^2 = A_s \cdot m^2; \]
\[ R_{sc,m} = R_{s,m} = R_{sc} = R_s; \quad R_{sn,m} = R_{sn}; \]
\[ R_{b,m} = R_b; \quad R_{bn,m} = R_{bn} \]

where \( A_s, A_{s,m} \) - are the area of the reinforcement in the tensioned and compressed zones of the column’s section accordingly, \( mm^2 \); \( R_s, R_{sc} \) - are the design resistance of the reinforcement to compression and tension accordingly, \( MPa \); \( A_{sn} \) - is the characteristic resistance of the reinforcement to tension, \( MPa \); \( R_{sn}, R_{bn} \) - are the design and characteristic resistance of concrete accordingly, \( MPa \).

The force similarity of the model, when determining the real column's strength, is expressed via the proportionality of the bending moment \( (M, \kappa H \cdot m) \), as in the equation (4):

\[ M_m = M \cdot m^3; \]

where \( M \) – is all-load bending moment, \( \kappa H \cdot m \); \( m \) – is the model’s similarity constant.

The force similarity of the model, when determining the real column’s fire resistance, is expressed via the proportionality of the long-term dead-load bending moment \( (M_{m, cou}, \kappa H \cdot m) \), as in the equation (5):

\[ M_{m, cou} = M_0 \cdot m^3; \]

where \( M_0 \) is the long-term test load bending moment, \( MPa \); \( m \) - is the model’s similarity constant.

To identify the strength of the model’s design section we should first determine:

a) the eccentricity of axial force \( (e_{o,m}, \ mm) \) - by equation (6):

\[ e_{o,m} = e_o \cdot m = (M_m/N_m) \cdot m; \]

b) the relative value of the model’s bending moment \( (\alpha_{M,m}) \) - by equation (7):

\[ \alpha_{M,m} = M_m/b_m \cdot h_{o,m}^2 \cdot (R_b/m^{1.5}); \]

where \( M_m \) – is all-load bending moment, \( \kappa H \cdot m \); \( b_m \) is the width of the model’s section, \( mm \); \( h_{o,m} \) - is the effective depth of the model’s section, \( mm \); \( R_b \) - is the design resistance of concrete to compression, \( MPa \); \( m \) - is the model’s similarity constant.

c) the factor of eccentricity growth caused by the model’s deflection \( (\eta) \) – by equation (8):

\[ \eta = 1 + \alpha_{M,m}; \]

d) the design bending moment in the model’s dangerous section \( (M_{\eta,m}, \kappa H \cdot m) \) with allowance for deflection – by equation (9):

\[ M_{\eta,m} = \eta \cdot M_m; \]

where \( M_m \) - is the design bending moment without allowance for the model’s deflection, \( \kappa H \cdot m \);

e) the top depth of concrete’s compressed zone \( (\xi_R) \) – by equation (10):
\[ \xi_R = 0,8/(1 + R_{s,m}/700); \]  

\[ f) \text{ the relative value of axial force } (\alpha_{N,m}) \text{ – by equation (11):} \]
\[ \alpha_{N,m} = N_m/b_m \cdot h_{o,m} \cdot R_b; \]  

where \( N_m \) - is axial force, \( kH \); \( b_m \) - is the width of the model’s section, \( mm \); \( h_{o,m} \) - is the effective depth of the model’s section, \( mm \); \( R_b \) - is the design resistance of concrete to compression, \( MPa \);

g) the depth of the model’s compressed section – by equation (12):
\[ x_m = \alpha_{N,m} \cdot h_{o,m}; \]

h) the strength of the model’s design section \( M_{cc} \, (kH \cdot m) \) – by formula (13):
\[ M_{cc} = m \cdot R_b \cdot b_m \cdot x_m \cdot (h_{o,m} - 0,5 \cdot x_m) + (R_{sc} \cdot A_{s,m} - 0,5 \cdot N_m) \cdot (h_{o,m} - a_m); \]  

where \( m \) - is the model’s similarity constant; \( R_b \) - is the design resistance of concrete to compression, \( MPa \); \( b_m \) - is the width of the model’s section, \( mm \); \( h_{o,m} \) - is the effective depth of the model’s section, \( mm \); \( R_{sc} \) - is the design resistance of the reinforcement to compression, \( MPa \); \( A_{s,m} \) - is the area of the model reinforcement’s section, \( mm^2 \); \( N_m \) - is axial force, \( kH \); \( a_m \) – is the laying depth of the model’s reinforcement, \( mm \);

i) the strength of the real column’s dangerous section \( M_{cc} \, kH \cdot m \) – by equation (14):
\[ M_{cc} = M_{cc,m}/m^3; \]

where \( M_{cc,m} \) - is the model’s design moment, \( kH \cdot m \); \( m \) – is the model’s similarity constant.

To identify the real reinforced concrete column’s fire resistance limit as a load-bearing capacity criterion, we should first determine:

a. the ratio of reinforcement in the model’s section \( \mu_{s,m} \) - by equation (15):
\[ \mu_{s,m} = A_{s,tot}/b_m \cdot h_m; \]

where \( A_{s,tot} \) - is the total reinforcement section area, \( mm^2 \); \( b_m \) - is the width of the model’s section, \( mm \); \( h_m \) - is the depth of the model’s section, \( mm \);

b. the ratio of saturation of concrete with working reinforcement \( (\alpha_\mu) \) – by equation (16):
\[ \alpha_\mu = \mu_{s,m} \cdot R_{sn}/R_{bn}; \]

where \( R_{sn} \); \( R_{bn} \) - are the characteristic resistance of the reinforcement, and accordingly of concrete, to compression, \( MPa \); \( \mu_{s,m} \) - is the ratio of reinforcement in the model’s section;

c. the depth of the model’s compressed section – by equation (17):
\[ x_m = \alpha_{N,m} \cdot h_{o,m}; \]

where \( \alpha_{N,m} \) - is the relative value of axial force for the model, \( mm \); \( h_{o,m} \) - is the depth of the model’s section, \( mm \);

d. the breaking bending moment in the model’s section under the conditions of a standard fire test \( (M_{pa,p,m}, kH \cdot m) \) – by equation (18):
\[ M_{pa,p,m} = m \cdot R_{bn} \cdot b_m \cdot x_{m,cou} \cdot (h_{o,m} - 0,5 \cdot x_{m,cou}) + (R_{sc} \cdot A_{s,m} - 0,5 \cdot N_m) \cdot (h_{o,m} - a_m); \]  

where \( m \) – is the model’s similarity constant; \( R_{bn} \) - is the characteristic resistance of concrete to compression; \( b_m \) - is the width of the model’s section, \( mm \); \( X_{m,cou} \) - is the depth of the section’s compressed zone, \( mm \); \( h_{o,m} \) - is the effective depth of the model’s section, \( mm \); \( R_{sn} \) – is the design
resistance of the reinforcement, MPa; $A_{s,m}$ - is the area of the model reinforcement’s section, $mm^2$; $N_m$ - is the axial force for the model, $kH$; $a_m$ – is the laying depth of the model’s reinforcement, $mm$;

e. the stress intensity in the model’s section ($J_{so}$) – by equation (19, 21):

$$J_{so} = M_{cou,m}/M_{pasp,m} \leq 1;$$

where $M_{cou,m}$ - is the ultimate bending moment in the model’s section under the conditions of a standard fire test, $kH\cdot m$; $M_{pasp,m}$ – is the breaking bending moment in the model’s section, $kH\cdot m$;

f. the duration of the model’s resistance ($\tau_{u(R),m}$, $min$) to standard fire effect – by equation (20):

$$\tau_{u(R),m} = \frac{5\cdot b_m^2 \cdot (1-0,6\cdot \alpha_{\mu}) \cdot (1-J_{so})^2}{D_{br}^2 \cdot R_{bn}^0 \cdot 0,25};$$

where $b_m$ - is the width of the model’s section, $mm$; $\alpha_{\mu}$ - is the ratio of saturation of concrete with working reinforcement; $J_{so}$ - is the stress intensity in the model’s section; $D_{br}$ - is the thermal diffusion indicator of concrete, $mm^2/min$; $R_{bn}$ - is the characteristic resistance of concrete to compression, $MPa$;

g. the real reinforced concrete column’s fire resistance limit as a load-bearing capacity criterion ($F_{u(R), min}$) – by equation (21):

$$F_{u(R)} = \tau_{u(R),m} / m^2;$$

where $\tau_{u(R),m}$ - is the duration of the model’s resistance to standard fire effect, $min$; $m$ - is the model’s similarity constant.

Designing and manufacturing a scaled model with a given similarity constant brings the scaled model’s test closer to the real column’s test and helps to identify the reinforced concrete column’s actual operation and its stress state from the beginning of the test and up to the stage of destruction. The development of the analytical model for calculating the actual fire resistance of the column excludes the fire tests of the model, and their replacement with non-destructive tests reduces the complexity of assessing the load-bearing capacity and fire resistance. Consequently, the conditions for testing the reinforced concrete column using its model are simplified.

The use of the analytical description of the process of resistance of the reinforced concrete column’s model to a standard fire test, as well as the use of the developed mathematical model, improve the accuracy and expressivity of the fire resistance assessment.

The method of identifying the load-bearing capacity and fire resistance of the reinforced concrete column using its model implies the following sequence of actions. First, the scaled model of the reinforced concrete column with a given similarity constant is designed, taking into account geometrical and force similarity; the geometric characteristics of the model and the real column are identified, as well as the strength characteristics of the specified reinforcement and concrete strength classes. The simulation efforts for identifying the load-bearing capacity and fire resistance of the column are determined, the thermal diffusion indicators of concrete are identified. The strength of the model’s and the real structure’s design section under normal operating conditions is identified, then - the failure moment value in the model’s and the real structure’s section under a standard fire test conditions, and next - the duration of the model’s resistance to fire test and the value of the real column’s fire resistance limit as a load-bearing capacity criterion.
Figure 1. The simulation scheme of the reinforced concrete column: a) the real column: rectangular section $b \times h$, $mm$ b) the scaled model of the column: the rectangular section with the dimensions $b_m \times h_m$, $mm$: $l$ and $l_m$ - are the length of the real column and the scaled model accordingly, $mm$; $N$ and $N_m$ – are the axial force acting on the real column and on the model accordingly, $kH$; $b \times h$ and $b_m \times h_m$ – are the width and depth of the section of the real column and the model accordingly, $mm$.

Figure 2. The scheme for calculating the strength model of the reinforced concrete column: the axial section (A-A), the cross section (B-B): 1 – is the column’s geometrical axis; 2 – is the border of concrete’s compressed zone; 3 – is the gravity center of the area of concrete’s compressed zone; 4 and 5 – are the axial reinforcement in the tensioned zone ($S$) and compressed zone ($S'$) accordingly; $b_m \times h_m$ – are the width and depth of the cross section, $mm$; $a_m$ and $a_m'$ - are the laying depth of reinforcement ($S$ and $S'$), $mm$; $A_{sm}$ and $A_{sm}'$ - are the area of the reinforcement’s section ($S$ and $S'$).
\( mm^2 \); \( e_{o,m} \) – is the eccentricity of the axial force acting on the model, \( mm \); \( x_m \) - is the depth of the model section’s compressed zone, \( mm \); \( Z_m \) - is the arm of couple of internal forces, \( mm \).

**Figure 3.** The fire resistance calculation scheme for the reinforced concrete column model’s rectangular section: the axial section, the cross section: 1 - is the model’s geometrical axis; 2 – is the border of the section’s compressed zone; 3 – is the gravity center of the area of concrete’s compressed zone; 4 and 5 – are the axial reinforcement in the tensioned zone \((S)\) and compressed zone \((S')\) accordingly; \( b_m \times h_m \) – are the width and depth of the model’s cross section, \( mm \); \( a_m \) and \( a_m' \) - are the laying depth of reinforcement \((S\) and \(S')\), \( mm \); \( R_b \) and \( R_{bn} \) – are the characteristic resistance of concrete and reinforcement to tension / compression accordingly, \( MPa \); \( e_{o,m} \) – is the eccentricity of axial force, \( mm \); \( x_m \) - is the depth of the model section’s compressed zone, \( mm \); \( Z_m \) - is the arm of couple of internal forces, \( mm \), \( t_{cm}, ° C \) - is the direction of the heat flow during a standard fire test.

The proposed method of identifying the load-bearing capacity and fire resistance of the reinforced concrete column using the model is required for the experimental evaluation of the target characteristics of compressed elements, when doing practical work at the applied research laboratory for reinforced concrete structures of the Academy of Civil Engineering and Architecture of SamSTU (Samara).

**3. Conclusion**

1. The actual operation of the reinforced concrete column and its stress state from the beginning of the test and up to the stage of destruction has been identified.
2. The quantitative characteristics of the load-bearing capacity and fire resistance of the modeling columns have been determined.
3. The load-bearing capacity of the column has been experimentally determined, and its fire resistance has been identified using non-destructive methods.
4. The experimental picture of the distribution of forces and the stress state in the column’s design section has been identified.
5. The reinforced concrete column’s limit state has been evaluated, according to its load-bearing capacity and fire resistance; the analytical model for calculating the actual fire resistance of the column has been developed.
6. The method of physical and analytical modeling has been developed for evaluating the fire resistance of the reinforced concrete column.

7. The tests of the scaled model, approximated to testing the real column of the building, have been carried out.

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