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DETERMINATION OF PARAMETERS OF AN EXPERIMENTAL MODEL OF A MULTI-STOREY STEEL FRAME

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Abstract: The load-bearing capacity of the structure can be accurately determined on large models made from the same material (or a material with similar elastic properties) as the actual structure. The scale of the model can be 1/5-1/6. This depends not only on the actual dimensions of the structure but also on the material of the model. Experience shows that for metal and concrete models, it is reasonable to adopt a scale of 1/5-1/15. Previous studies show that analysis based on the calculation of an idealized multi-story steel frame structure without considering imperfections does not fully reflect the actual performance of the steel frame and may not always ensure the load-bearing capacity of the building and the operational requirements for permissible frame displacements. It is interesting to compare some approximate data on the cost of testing in kind with the cost of testing the model. Thus, full-scale tests of large-panel buildings erected on subsidence soils ac-count for 10 to 30% of the cost of the buildings themselves. The cost of such tests on models would be 2-3%, that is, 5-10 times cheaper. The provided data indicates the feasibility of using modeling in the design of structures. The research results can be used to refine and develop building codes and standards, enabling the calculation and design of multi-story buildings that account for the actual performance of the steel frame-work.

Keywords: multi-storey buildings, installation and Fabrication errors, rigid frame, steel constructions, linear calculation, nonlinear calculation, geometric imperfections

ОПРЕДЕЛЕНИЕ ПАРАМЕТРОВ ЭКСПЕРИМЕНТАЛЬНОЙ МОДЕЛИ МНОГОЭТАЖНОГО СТАЛЬНОГО КАРКАСА

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Аннотация: Несущую способность конструкции можно достаточно точно определить на крупных моделях, изготовленных из того же материала (или близкого к нему по своим упругим свойствам), что и сама конструкция. Масштаб модели может быть 1/5-1/6. Это зависит не только от натурных размеров сооружения, но и от материала модели. Опыт показывает, что при металлических, бетонных и армоцементных моделях масштаба целесообразно принимать 1/5-1/15. Проведённые ранее исследования показывают, что анализ, основанный на расчете идеализированной многоэтажной стальной каркасной конструкции без учёта несовершенств, не полностью отражает действительную работу стального каркаса и не всегда может обеспечить несущую способность здания и эксплуатационные требования по допустимым перемещениям каркасов. Интересно сопоставить некоторые примерные данные стоимости испытаний в натуре со стоимостью испытания модели. Так, натурные испытания крупнопанельных зданий, возводимых на просадочных грунтах, составляют от 10 до 30% стоимости самих зданий. Стоимость подобных испытаний на моделях составила бы 2-3%, т.е. дешевле в 5-10 раз. Приведенные данные указывают на целесообразность использования моделирования при проектировании сооружений. Результаты исследований могут быть использованы для уточнения и разработки строительных норм и стандартов, что даст возможность расчёта и проектирования многоэтажных зданий с учётом действительной работы стального каркаса.

Ключевые слова: многоэтажные здания, погрешность монтажа и изготовления, рамный каркас, стальные конструкции, линейный расчет, нелинейный расчет, геометрические несовершенства

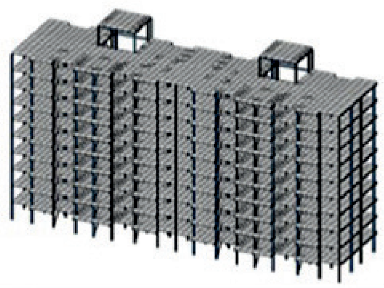
INTRODUCTION

A significant portion of urban development consists of multi-story buildings. These buildings can be categorized as public, industrial, or residential based on their purpose. Buildings over 75 meters in height are referred to as high-rise buildings, while those exceeding 100 meters are considered unique structures. [1-2]. Multi-storey buildings are characterized by the fact that a large building is being built on a relatively small area of development. The steel frame of a multi-storey building is a spatial system of load-bearing structural elements of the rod type, providing its necessary rigidity, stability and strength. In addition to columns, floor beams and vertical connections, hard disks of floors are formed, ensuring effective load transfer to vertical connections [3-6]. The choice of the structural frame scheme affects material consumption, building cost, operational expenses, and assembly labor intensity. In addition to ensuring the load-bearing capacity of the frame, it is essential to eliminate excessive horizontal and vertical displacements as well as unacceptable fluctuations [7-8]. The experience and practice of constructing multi-story steel frames in residential buildings in the Russian Federation are still limited. It is necessary to develop structural solutions that ensure fast and high-quality frame montage. The frame, mounted even from perfectly made structures, often has deviations of the columns from the vertical position, which leads to a decrease in the bearing capacity of the structure [9-10].
The load-bearing capacity of the structure can be accurately determined using large-scale models made from the same material (or a material with similar elastic properties) as the actual structure. The scale of the model can be 1/5-1/6. This depends not only on the actual dimensions of the structure but also on the material of the model. This depends not only on the actual dimensions of the structure but also on the material of the model. Experience shows that for metal and concrete models, it is reasonable to adopt a scale of 1/5-1/15.

The relevance of the work is to study the effect of the installation error on the operation of the steel frame of a multi-storey building. The research results can be used to refine and develop building codes and standards, enabling the calculation and design of multi-story buildings that account for the actual performance of the steel framework.

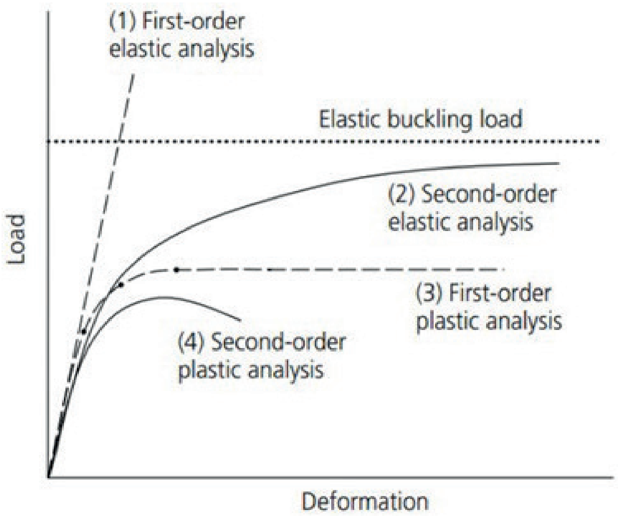
METHODS

The calculation of steel frames can be performed using several methods (Fig.1).



	Perfect shape	Initial imperfections	Linear material	Non-linear material
(1) Fist-order elastic analysis	x		x	
(2) Second-order elastic analysis		x	x	
(3) First-order plastic analysis	x			x
(4) Second-order plastic analysis		x		x

a) Different structural analysis methods



b) Load-deformation curve for different analysis types

Figure 1. General characteristics of steel frame calculation methods [11-14]

1. Calculation in an elastic formulation without taking into account the geometric nonlinearity of the structure – First-order elastic analysis.
2. Calculation in an elastic formulation taking into account the geometric nonlinearity of the structure – Second-order elastic analysis.
3. The calculation takes into account the physical nonlinearity of the material (the development of plastic deformations of steel is allowed), but without taking into account the geometric nonlinearity of the structure – First-order plastic analysis.
4. Calculation taking into account physical and geometric nonlinearity – Second-order plastic analysis.

Previous studies show that the analysis based on the calculation of an idealized multi-storey steel frame structure without taking into account imperfections does not fully reflect the actual operation of the steel frame and cannot always provide the bearing capacity of the building and the operational requirements for permissible movements of the frames [15-16].

The evaluation of the testing of the frame with rigid conjugations in reality was performed using the example of the frame of a 6-storey residential building. The height of the floor is 3.0 m. In the transverse direction, the frame consists of 3 spans, the step of the columns is 8.0 m. Steel columns and beams C345 (Fig.2). The columns of the frame are made of I-beams 20K2, crossbars of I-beams 40B1.

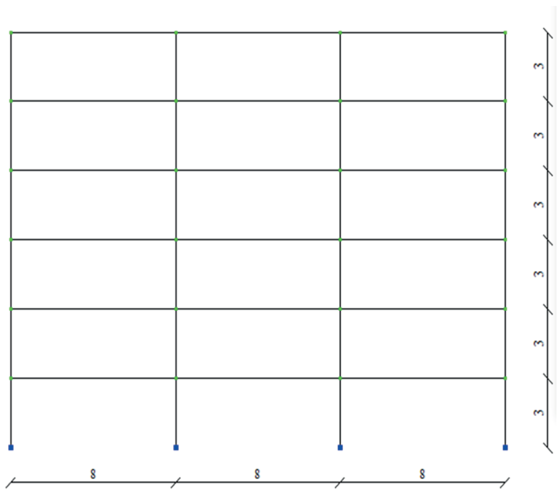


Figure 2. Geometry of the full-scale frame

A multi-storey frame structure was developed to test the multi-storey frame in the laboratory. The total number of floors in the model is 6, the frame with rigid conjugations , the floor height is 0.45 m. In the transverse direction, the frame consists of 3 spans, the step of the columns is 1.2 m. The steel of the columns and beams is C245 (Fig.3). The columns of the frame in the model are made of square pipes 45x5 mm, crossbars of rectangular pipes 70x50x5 mm.

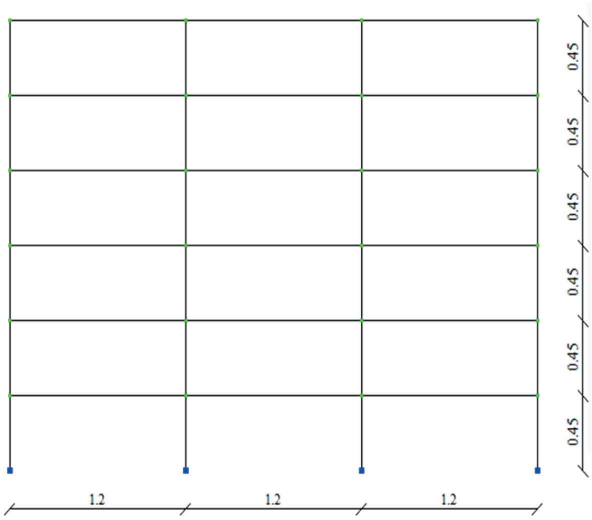


Figure 3. Geometry of the frame model

The frame is a load-bearing core system in which the columns and beams are rigidly connected to each other, and the columns are rigidly attached to the foundation. Due to the rigid attachment of the frame elements to each other, spatial stability and rigidity in the plane of the transverse frame are ensured.

The weight of the steel frame is taken into account by the cross sections of the elements when calculating by computing complexes. When determining the load from the own weight of the frame, the load reliability coefficient equal to 1.05 and the construction coefficient 1.2 are taken into account, taking into account the presence of ribs, linings, shapes and support plates. The load on the steel floor crossbars is determined taking into account the width of the loading area equal to the step of the transverse frames.

For the IV snow region, the normative snow load is 2.0 kPa, the calculated 2.8 kPa. For the IV wind region, the standard wind pressure is 0.48 kPa. The calculated wind load on the frame is determined taking into account the current norms and is 0.59 kPa for the top of the frame. In terms of bearing capacity, the distribution of wind load over the entire height of the building is assumed to be constant and equal to the value of the wind load at the top of the building.

To carry out the calculation, a finite element core model of the frame for a flat frame was formed. The calculation was performed using the LIRA-CAD 2021 computing complex. Table 1 shows the types of stiffness of the finite elements of a full-scale multi-storey frame.

Table 1. Types of stiffness of the frame elements

Type of stiffness	Name of the element	The cross section in reality
1	Columns	20K2[1]
2	Beams	40B1[2]

The load[3] was applied to the calculation scheme in the form of 5 loads:

1 loading: dead load – the weight of load-bearing structures;

2 loading: dead load – the weight of the enclosing structures;

3 Loading: live load;

4 loading: snow load;

5 Loading: wind load.

For the main load-bearing elements of the frame (columns and beams) the stress state is described by the formula

For the main load-bearing elements of the frame (columns and beams) the stress state is described by the formula

$$\sigma = \frac{N}{A} \pm \frac{M}{W} \quad (1)$$

where N – axial force, M – bending moment, A – cross-sectional area, W – the moment of resistance of the section.

The geometric dimensions of the model are taken from the condition of its placement in the laboratory. The scale of the model is 1.2/8=0.45/3=0.15. The section of the column was chosen taking into account the adopted design decision of the frame attachment points to the power floor. These parameters are used as the initial parameters for determining the remaining characteristics of the model.

Let's determine the remaining parameters of the laboratory model from the conditions of similarity of a full-scale multi -storey frame . since the effect of the column deviation from the vertical on the operation of the frame is being investigated, first of all, the stress-strain state of the column will determine the parameters of the laboratory structure.

Normal stresses in the column arise from the action of an axial force and a bending moment, which can be represented as the sum of two moments: from the eccentric action of the axial force and bending moment from the horizontal load.

$$\sigma = \frac{N}{A} \pm \frac{(Ne + kTH)}{W} \quad (2)$$

where e – the eccentricity of the axial force application, T – horizontal force equivalent to wind load, k – the fraction of the moment of the horizontal force in the column under study, H – building height.

Let's transform this expression to a dimensionless form. Let's introduce scale transformations for all values included in the specified expression,

$$\sigma = \sigma_0\bar{\sigma};\ N = n_0\overline{N};\ A = a_0\bar{A};\ T = n_0\overline{T};\ e = l_0\bar{e};\ H = l_0\overline{H};\ W = w_0\overline{W} \quad (3)$$

1 GOST R 57837-2017. Hot-rolled steel I-beams with parallel shelf faces. Technical conditions

2 GOST R 57837-2017. Hot-rolled steel I-beams with parallel shelf faces. Technical conditions

3 SP 20.13330.2016. Loads and impacts. (Updated version of SNiP 2.01.07—85*.)

Here, the "O" index marks the scales, and the letters with dashes at the top indicate the corresponding dimensional values.
Let the choice of scale be unlimited for now. Substituting these transformations into the initial expression, we get:

$$\sigma_0 \bar{\sigma} = \frac{n_0 \overline{N}}{a_0 \overline{A}} \pm \frac{n_0 l_0 (\overline{N} \bar{e} + k \overline{T} \overline{H})}{w_0 \overline{W}} \tag{4}$$

In order for equation (4) to become dimensionless, the condition must be fulfilled:

$$\sigma_0 = \frac{n_0}{a_0} = \frac{n_0 l_0}{w_0} \tag{5}$$

This equality, which represents a restriction imposed on the freedom to choose scales, is called the coupling equation. The equation contains two coupling equations and five scales. Therefore, three scales can be chosen arbitrarily, and two are found from the coupling equations as functions of three arbitrary scales.
Values $\frac{n_0}{a_0 \sigma_0} = 1$ and $\frac{n_0 l_0}{\sigma_0 w_0} = 1$, obtained from the coupling equations are called similarity criteria.
The initial equation (1), which determines the stress state of the frame, can be represented in a dimensionless form. A dimensionless equation called the law of similarity:

$$\bar{\sigma} = \frac{\overline{N}}{\overline{A}} \pm \frac{\overline{M}}{\overline{W}} \tag{6}$$

The number of independent coupling equations (t) is less than the number of scales (n). Therefore, some of the scales can be chosen arbitrarily, and the rest can be determined using coupling equations. At the same time, there should be no scales with interdependent dimensions among the arbitrarily selected scales. So, for example, if, among arbitrary scales, we choose the scale of force n_0, the scale of the cross sectional area a_0 и σ_0 — the stress scale, then an arbitrary choice of any two of them would already determine the choice of the third one due to the ratio

$$\sigma_0 = \frac{n_0}{a_0} \tag{7}$$

$$\sigma_0 = \frac{n_0 l_0}{w_0} \tag{8}$$

In the above scale restriction condition, we can choose three arbitrary non-interconnected scales, for example σ_0; a_0; m_0, and the remaining scales will be determined from the coupling equation.
Thus, arbitrarily selected scales should have independent dimensions.
From the example considered, it can be seen that with the help of scale transformations, at the same time, the choice of scales must be subordinated to the following restrictions:
From the total number of *n*-scales, you should choose arbitrarily *k*-scales with independent dimensions; as arbitrarily selected scales, the corresponding parameters should be taken from among the terms included in the considered physical equation; n — k-scales, having dependent dimensions, they must be determined by solving the coupling equations that are obtained by introducing scale transformations into the original physical equation [17-18].

RESULTS AND DISCUSSION

In the table 2 the characteristics of the cross sections of the columns of nature and model are presented.

Table 2. Characteristics of column cross sections

Type of columns	Profile	(A), cm^2	(W), cm^3
Nature	20K2	63,53	471,60
Model	45x5 mm	7,57	8,38

Taking into account the given dimensions at the beginning of the article (Fig. 2 and 3), we find l_0:

$$l_0 = \frac{\bar{e}}{e} = \frac{\overline{H}}{H}$$

$$l_0 = \frac{1{,}2}{8} = \frac{0{,}45}{3} = 0{,}150$$

Taking into account the geometric characteristics of the column of the full-scale structure and the model, we determine the scales for the cross-sectional area and the moment of resistance:

$$a_0 = A/\bar{A}$$
$$a_0 = \frac{7{,}57}{63{,}53} = 0.119$$
$$w_0 = W/\overline{W}$$
$$w_0 = \frac{8{,}38}{471{,}60} = 0.0178$$

From equation (7) and assuming $\sigma_0 = 1$, we get this

$$a_0 = n_0 \tag{9}$$
$$n_0 = 0.119$$

Let's check whether the selected column of the model satisfies the similarity criteria of equation (5, 7, 8).

Fulfilling the condition (7):

$$\sigma_{0column} = \frac{0{,}119}{0{,}119} = 1$$

Fulfilling the condition (8):

$\sigma_{0column} = \frac{0{,}119 \cdot 0{,}15}{0{,}0178} = 1{,}002 \approx 1$. The margin of error is less than 1%

Let's define the required beam parameters:

$$A_{beam} = 0.119 * 72.16 = 8.60 \text{ cm}^2$$
$$W_{beam} = 0.0178 * 1011.1 = 18.00 \text{ cm}^3$$

A rectangular tube with a cross section has the closest area and moment of resistance 70x50x5.

In the table 3 the characteristics of the cross sections of the beams of nature and model are presented.

Table 3. Characteristics of cross sections of beams

Type of beams	**Profile**	**(A), см^2**	**(W), см^3**
Nature	40B1	72,16	1011,10
Model	70x50x5	10,57	18,84

The error for the selected profile in terms of cross-sectional area is (10.-8.6)/8.6 = 22.91%, by the moment of resistance (18.84-18)/18 = 4.67%, Due to the fact that, first of all, the bending characteristics of the beam determine the moment transmitted to the column.

The selected profiles are accepted for further construction of the model structure.

In the table 4 shows the scale factors used in the development of the model.

Table 4. Scale factors for columns

The scale factor of the dimensions	l_0	0,150
Stress scale factor	σ_0	1,000
The scale factor of the force	n_0	0,119
Area scale factor	a_0	0,119
The scale factor of the moment of resistance	w_0	0,0178

CONCLUSION

It is interesting to compare some approximate data on the cost of testing in kind with the cost of testing the model. Thus, full-scale tests of large-panel buildings erected on subsidence soils account for 10 to 30% of the cost of the buildings themselves. The cost of such tests on models would be 2-3%, that is, 5-10 times cheaper.

These data indicate the expediency of using modeling in the design of structures.

In order to effectively use modeling methods in building design, it is necessary, in addition to developing research methodology issues, to improve existing ones, create special measuring equipment and devices, generalize experience and develop a number of new methods of model manufacturing technology, have specialized production groups for model manufacturing in laboratories.

It should be noted that in order to determine the parameters of the experimental model, it is important first of all to calculate the scale coefficients of the frame size (l_0), area (a_0) and moment of resistance (w_0) based on the available data. The geometric dimensions of the model are taken from the condition of its placement in the laboratory. The section of the column was chosen taking into account the adopted design decision of the frame attachment points to the power floor.

When checking whether the matched column meets the similarity criteria, the error turned out to be less than 1%. When checking the satisfaction of the selected beam with the similarity criteria based on the scale coefficients of the column, an error of 22.91% was found.

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