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METHODOLOGICAL ASPECTS OF ASSESSING THE STEEL FRAMES RELIABILITY

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The article highlights the proposed algorithm for evaluating the reliability of steel frames. In particular, it is possible to analyze the reliability of the most likely failure mechanism. Separate assumptions that determine the sequence of application of the limit equilibrium method are presented. A method for determining the reliability of statically indeterminate steel frames in the plastic stage is presented. This method provides an opportunity to determine the probable mechanism of destruction. The ultimate equilibrium method is used to calculate the forces at the final stage of destruction. In the work, the real mechanism of destruction is understood as a mechanism for which the work of external forces to create it is the least. It is revealed that the real mechanism of destruction is approaching the beam or floor elementary mechanism.

Keywords: reliability, failure mechanism, steel frames, calculation.

МЕТОДИЧНІ АСПЕКТИ ОЦІНЮВАННЯ НАДІЙНОСТІ СТАЛЕВИХ РАМ

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Стаття висвітлює запропонований алгоритм оцінювання надійності сталевих рам. Зокрема, приведена можливість аналізу надійності за найбільш ймовірним механізмом руйнування. Представлені окремі припущення, які визначають послідовність застосування методу граничної рівноваги. Представлено методику визначення надійності сталевих статично невизначених рам у пластичній стадії. Така методика надає можливість визначення ймовірного механізму руйнування. Методом граничної рівноваги розраховуються зусилля на кінцевій стадії руйнування. В роботі під реальним механізмом руйнування розуміється механізм для якого робота зовнішніх сил по його створенню буде найменшою. Виявлено, що реальний механізм руйнування наближається до балкового або поверхового елементарного механізму. В статті розрахунки на початковому етапі виконані в детерміністичній постановці для сталевих рам методом граничної рівноваги Отримані чисельні граничних моментів, зокрема для граничного етапу реального механізму руйнування. Розроблена програма, яка надає результати розрахунку сталевих рам за двома напрямами. Один напрям орієнтований на суто задані чисельні значення жорсткостей. Окремо визначаються граничні моменти та значення моментів у перерізах. Такий метод визначає реальну картину руйнування. Інший напрям розрахунку направлений на оптимізацію розрахунку та мінімізацію показників маси конструкції. Представлена можливість розгляду різних випадків руйнування сталевих рам. А головна перевага даного методу знаходження найбільш реального механізму руйнування. Такі методи є важливим елементом проектування нових сучасних конструктивних форм та визначення слабких місць уже існуючих конструкцій.

Ключові слова: надійність, механізм руйнування, сталеві рами, граничні моменти.

Introduction

Considering the general information about the reliability assessment of steel frames, it is noted that the distribution of forces during plastic destruction does not depend on the loading history, on the behavior of the structure before its complete plastic destruction. Therefore, for the calculation of steel statically indeterminate frames made of elastic - plastic material, we can only consider the phase of exhaustion of the bearing capacity of structures, their plastic destruction. This position is used in the calculation using the limit equilibrium method.

Review of research sources and publications

In general, norms in Ukraine [1] set the general principles for ensuring the reliability and structural safety of buildings and structures. These rules apply to the search, design, construction and disposal of buildings and structures, regardless of their purpose.

The issue of reliability of steel frames is presented in the works of various leading scientists of the world. In particular in the work [2] concerns the underpinning system reliability calibrations that enables the implementation of the next generation of system-based design-by-analysis method of steel rack frames, i.e., a design approach where analysis and capacity checks are carried out in a single step by using fully nonlinear analysis. The paper details the design framework of the new approach, referred to as the Direct Design Method (DDM), and derives system strength statistics for five typical configurations of rack frames using Monte-Carlo simulations, considering the randomness of geometric and material properties. The nominal models of rack frames are developed in accordance with the Australian Standard AS4084. The mean-to-nominal ratios (bias) and coefficient of variation of the system strengths are obtained, and is used in the companion paper to derive the system resistance factors consistent with a given structural reliability. In the second of two works [3] introducing the underpinning structural analyses and reliability studies that implement the system-based design-by-analysis method of steel rack frames, referred to as the Direct Design Method (DDM). The present paper presents the reliability analyses and derivation of system reliability index (β) versus system resistance factors (ϕ_s) curves. Results are presented for nominal system strengths as per Australian Standard AS4084 for several nominal models, including models that exclude sectional imperfections, and models without member and sectional imperfections. The effect of model uncertainty is also assessed. A detailed example of the DDM applied to the design of a rack frame is presented and the benefits of the DDM are demonstrated when compared to the traditional design approach which is based on elastic analysis. In the [4], the authors note that high strength bolted end-plate connection is main type of the connections used widely in industrial construction. There are two kinds of end-plate connections in steel portal frames: flush and extend end-plate connections. The main initial imperfection of bolted end-plate connection lies in which the thickness of end-plate and column flange can't meet the code provisions based on a field investigation. Considering the effect of initial imperfection, the actual behavior of end-plate connections in steel portal frames is seldom fully rigid. The true behavior of the connections is usually semi-rigid. Neglecting the real behavior of connections in the analysis may lead to unrealistic predictions of the response and reliability of steel portal frames. The paper [4] considers the effects of semi-rigid behavior of the connections in the finite element analysis and reliability analysis of steel portal frames. Assuming that the loads and the resistance of members are random variables, then the Monte Carlo simulation technique is used to estimate the failure probability of steel portal frame system. The results confirm that the thickness of end-plate has a significant effect on safety of steel portal frame. Integrated structural designs, with consideration of system reliability for steel portal frames comprising tapered members, are studied in the paper [5]. The reliability-based integrated design (RID) directly checks the structural system limit states and the corresponding system reliability, based on structural nonlinear analysis. The nonlinear integrated analysis model, the semi-analytical simulation method employed for system reliability assessment, the development processes of RID format and the design application of RID formula and curves are presented in this paper. Design examples and comparisons among three different design formats demonstrate that RID proposed in this paper is of certain and consistent system reliability levels, and provides a feasible way for structural engineers to improve the design quality and flexibility of steel frame structures. Progressive collapse is an important failure mechanism that must be considered in the design of critical and essential buildings [6]. For steel moment structures, beam-column joints, which act as transportation hubs of forces, are crucial members to resist progressive collapse. This research [6] investigated the effectiveness of beam-column joints with cast steel stiffeners (CSS) in steel moment frames for progressive collapse resistance. A computationally efficient macromodel that can be used for routine design of steel moment frame buildings with CSS was developed in this paper. The developed model, which considers the deformation of joints with CSS and the catenary action effects during progressive collapse, was validated using a 3D solid finite-element model. Subsequently, the macromodel was utilized to calculate the proper dynamic increase factor for steel moment frame structures with beam-column joints using CSS. The results show that the frame with CSS is less vulnerable to gravity-induced progressive collapse than frames with welded beam-column joints without stiffeners. The proposed macromodel is effective and a dynamic increase factor of 1.6 is suitable for dynamic progressive collapse analysis of steel moment frame structures using beam-column joints with CSS.

The work [7] reviews the state-of-art in progressive collapse studies on framed building structures. Such types of failure start with a local damage which extension increases, up to the whole structure. First emphasis is placed on the current techniques to study collapse propagation, i.e., numerical, experimental and analytical. In particular, the various numerical methods found in the literature are reported and discussed and the experimental studies and technologies involved in the laboratory tests are listed and compared. As reviewed, the method of analysis depends on the collapse mechanism and the triggering event. Thus, an in-depth review of the collapse typologies is proposed. Pure and mixed progressive collapse mechanisms are discussed and debated. The various triggering events, their modeling and their effects on the framed structures are examined. Details on the available literature on multi-hazard scenarios are provided. Finally, robustness techniques against progressive collapse are summarized, compared and contrasted. The paper [7] concludes with an ambitious comprehensive list of open questions and issues covering different aspects of future needs.

Definition of unsolved aspects of the problem

In the literature, there are not enough disclosed questions on the formulation of the term "survivability", not presented a single algorithm for calculating the survivability of building structures. Also, the literature does not consider the dynamic components of the load on steel redundant frame.

Problem statement

When determining the reliability of steel statically indeterminate frames by the method of limit equilibrium in this paper it is necessary to make some assumptions:

1. Application loads are of the quasi-static type. Dynamic defects and re-variable loading were not considered.

2. The construction Material is ideally elastic-plastic and obeys the Prandtl diagram. It can be noted that the ideal plasticity is the first approximation for the real behavior of the structure beyond the elastic limit and corresponds to this method of limiting equilibrium is quite suitable for solving problems of determining the load-bearing capacity. Considering the actual operation of a statically indeterminate steel frame, it can be concluded that it is close to an ideal elastic-plastic one. The strength distribution of the material was assumed to be normal, which corresponds to the experimental data obtained during the tensile testing of steel samples.

3. Deformations at destruction are small, so the equilibrium equations are made for an underformed scheme. It is known that this assumption is always accepted when elastic calculation of structures does not cause doubts about the insignificance of errors. It is assumed that when considering one-, two-, and three-story multi-span frames, horizontal deformations are small.

4. The sections of the elements have an ideal shape, for such a section, the plastic section occurs simultaneously over the entire area, as a result of which the zone of the plastic hinge is limited to a point. This assumption enables to assume that the destruction mechanism is a kinematic chain consisting of solid particles connected in certain places by hinges. This assumption makes it much easier to kinematically consider the system, the closer to reality the cross-sections of elements are closer to the ideal cross-section, which is most acceptable in metal structures, because thin-walled profiles close to I-beams are used.

5. The main acting forces are bending moments, and the basis for determining the bearing capacity is the strength criterion. The action of transverse forces in the formation of the destruction mechanism is not taken into account, since their influence is small. Accounting for the longitudinal force for columns is possible and is considered as a fraction of the maximum bending moment.

Basic material and results

When determining the reliability of structures, a reasonable approach should be taken. This approach takes into account all aspects that determine its load-bearing capacity and Express real work under current loads. Based on the results of probabilistic calculations and experimental studies, a number of the above-listed assumptions can be accepted for the reliability of the results. The reliability of statically indeterminate steel frames operating in the plastic stage can be assessed with sufficient confidence by examining one of the most likely mechanisms of structural failure. The proposed calculation method allows us to obtain this one most likely (true) mechanism of structural failure. To determine the forces in the final phase of destruction, the method of limiting equilibrium is used, which can be expressed as the equality of the virtual work of external A_{sx} and internal forces A_{in}:

$$A_{sx} = A_{in}\,; \tag{1}$$

$$\sum_j P_j f_j = \sum_k M_{pl,k} V_k \;, \tag{2}$$

where P_j is the value of the *j-th* external load in the form of a concentrated force, distributed load, or moment;
$M_{pl,k}$ is the plastic moment in the *k-th* section when forming a plastic hinge;
f_j is the turns or moves of nodes;
v_k is the turns of rods in the *k-th* section.

For a static formulation of the problem of determining internal forces when the load-bearing capacity of the frame is exhausted, the one for which the work of internal forces reaches the lowest value is accepted out of all the statically acceptable ones. A mathematical model of the problem of calculating an elastic-plastic system, characterized by a single parameter *min* M_o, from a one-time simple load, can be expressed

$$\left.\begin{array}{l} \mu_i \cdot M_o - M_i \ge 0 \\ \mu_i \cdot M_o + M_i \ge 0 \end{array}\right\} i = 1,2,..n\,, \tag{3}$$

where M_i is the moment acting in the I-th dangerous section;
M_o is the parameter of the maximum bending moment;
μ_i is the component of the vector of coefficients of ratios of the system's load-carrying capacity characteristics are set

$$\sum_{i=1}^{n} \propto_{ij} M_i = P_i \text{ , } (j = 1, 2, \ldots (n\text{-}k)), \quad (4)$$

where $\alpha_{i,j}$ is the element of the matrix of equilibrium conditions;
P_j is the component of the external load vector;
k is the degree of static uncertainty of the system;
n is the number of suspected dangerous sections.

Condition (3) is considered as a linear programming problem that is solved by the simplex method. For the elastic-plastic calculation of flat frames, a program was written in the FORTRAN language, in which two calculation modes are performed.

One direction is focused on strictly specified numerical values of stiffness. Separately determined by the marginal moments and the values of the points in the sections. This method determines the real picture of destruction.

Second, when the frame is optimized for a given number of stiffness ratios ($\leq n$) to obtain the minimum moment distribution by changing the stiffness ratio, the result is a minimum weight design. Let's focus on the first mode, which shows the true mechanism of destruction (the most likely). To perform calculations of statically indeterminate steel frames by the simplex method, it is necessary to create elementary equilibrium equations (in the static formulation of the equation together) for the specified geometric dimensions of the structure, the ratio of stiffness characteristics, the magnitude and direction of external loads. In connection with the different methods of composing equations in the literature, we present a generalized version of their Assembly (Fig. 1 - 2).

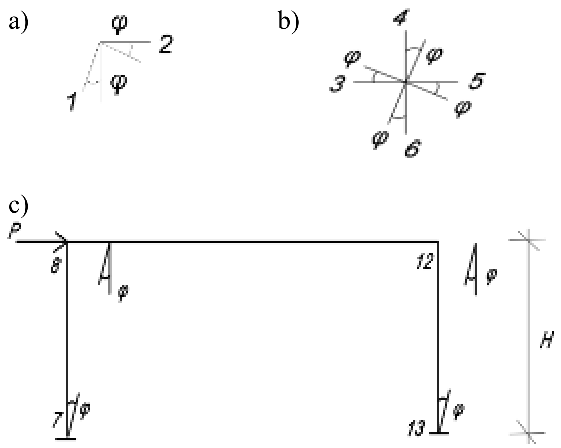

Figure 1 – Nodal (sum of moments in a node):
a) $M_1 + M_2 = 0$; b) $M_3 + M_4 + M_5 + M_6 = 0$;
c) surface (sliding),
(the shear force of the floors or stairs):
$M_7 – M_8 - M_{12} - M_{13} = P\,H$

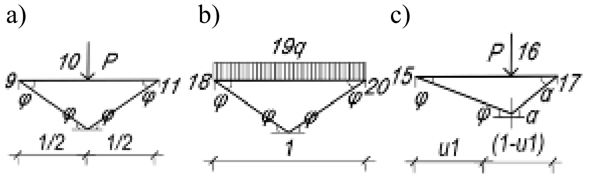

Figure 2 – Beam (the value of the bending moment for the cross section on the rod through the moments at the ends:
a) $M_9 + 2M_{10} + M_{11} = PL/2$;
b) $M_{18} + 2M_{19} + M_{20} = qL^2/2;$
c) $M_{15}+M_{16}+uM_{17}=PL(1-u)$

The calculation of steel statically indeterminate frames by the method of limiting equilibrium in the initial stage is performed in a deterministic setting. In the process of calculations, we obtain the values of the limiting moments in the frame sections for the boundary phase of destruction for the true mechanism. A true mechanism is a mechanism for which the work of external forces to create it is the least. For this calculation, the true mechanism is the one for which the value of the Mo limit moment is the smallest. Probabilistic characteristics of strength and load are introduced at the final stage of calculating the probability of failure of the system as a whole. Based on the joint solution, a method for calculating the reliability of statically indeterminate frames is obtained, in which the conditions for plasticity hinges have the form of equations describing hyperplasticity in *(k + 1)* – dimensional hyperspace

$$\sum_{j=1}^{k} M_{ij} x_j + qM_{io} \leq M_{i,pl} \text{ , } (j = 1, 2, \ldots) \quad (5)$$

where $M_{i,pl}$ is the limit moment in the *i-th* section;
$M_{i,j}$ is the moment in the *i-th* section of the main system from the excess unknown $x_j = 1$;
M_{i0} is the moment in the i-th section from external loads q, whose parameter is assumed to be $q=1$.

The intersection of the hyperplanes defines the vertex of the polyhedron of conditions for which the maximum load value is determined

$$q = q_{max} \text{ .} \quad (6)$$

From the solution of (k+1) linear equations (5) with substitution of the average limiting moments $M_{r,pl}$ in the right part and transition to the area of random parameters, we obtain the mathematical expectation of the frame strength as a whole in the space of the load parameter

$$\overline{q} = \sum_{r=0}^{k+1} \frac{A_{r,k+1}}{D} \overline{M}_{r,pl} = \sum_{r=1}^{k+1} \frac{A_{r,k+1}}{D} \mu_r \overline{M}_{0,pl} \text{ ,} \quad (7)$$

where D is the determinant of the system of equations;
$A_{r,k+1}$ is the algebraic extensions of elements $M_{r,pl}$ of the determinant D;
$M_{o,\,pl}$ is the average value of the frame limit moment parameter;
μ_r is the component of the vector of coefficients of the frame limit moments ratios;
r is the number of the plasticity hinge.

The frame strength standard in the load parameter space is determined by

$$\hat{q} = \sum_{r=0}^{k+1} \frac{A_{r,k+1}}{D} \hat{M}_{r,pl} = \sum_{r=1}^{k+1} \frac{A_{r,k+1}}{D} \mu_r \hat{M}_{0,pl} \ . \quad (8)$$

Expressions (7) and (8) determine the numerical characteristics of the random strength of the frame as a whole in the space of the load parameter, depending on the random characteristics of the random strength of individual elements when the frame is loaded once, when all loads and boundary moments are proportional to one parameter. The distribution of plastic moments in the frame $M_{r,pl}$ and the value of the limit plastic moments $M_{o,pl}$ are determined by the simplex method using the SIMPLEX program.

If the load parameter is a random value◦ $\tilde{Q}$, the frame strength reserve is equal to

$$\tilde{S} = \tilde{q} - \tilde{Q} > 0 \, , \quad (9)$$

mathematical expectation of the strength reserve

$$\overline{S} = \overline{q} - \overline{Q} > 0 \, , \quad (10)$$

the average square deviation of the strength reserve

$$\hat{S} = \sqrt{\hat{q}^2 + \hat{Q}^2} \ . \quad (11)$$

Dependence of the calculated load characteristics and limit plastic moments on the corresponding characteristics of random parameters:

$$Q = \overline{Q} + \gamma_Q \hat{Q} \ ; \quad (12)$$

$$M_{0,pl} = \overline{M}_{0,pl} - \gamma_q \hat{M}_{0,pl} \, , \quad (13)$$

where $M_{0,pl}$, $\overline{M}_{0,pl}$, $\gamma_q \hat{M}_{0,pl}$ are the calculation, mathematical expectation, standard of the limit moment value;

Q , $\overline{Q}$, $\hat{Q}$ are the calculation, mathematical expectation, standard of the limit moment value.

γ_Q , γ_q are the the number of standard deviations from the average for the design load and strength.

Conclusions

Determining the reliability of systems as a whole by one mechanism is numerically quite justified, but there may actually be mechanisms that have the probability of appearing close to the most likely mechanism. Therefore, the responsibility of the elements that make up these mechanisms is as significant as the elements that make up the true mechanism. In this regard, it is necessary to consider all the most likely mechanisms of destruction to better account for the load-bearing capacity of all structural elements in the design of new and reconstruction of existing buildings.

In general, it is possible to consider various cases of destruction of steel frames. And the main advantage of this method of finding the most real mechanism of destruction. Such methods are an important element of designing new modern structural forms and identifying weaknesses in existing structures.

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