Assessment of mechanical safety of cost-optimized reinforced concrete structures

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Abstract. The methods for evaluation of the optimality degree and the level of mechanical safety of design solutions are considered as an example of a reinforced concrete frame. Integrated safety margins of rigidity and stability are introduced, which are calculated according to the inherent structural sections formed as a result of discretizing the object into finite elements. The methods provide for the possibility of such an evaluation for relatively simple structures and without the finite element method. Using the example of a reinforced concrete framed stack, an evaluation of four design solutions obtained for various operating conditions by the normal designing and using an adapted genetic algorithm is illustrated.

1. Introduction

One of the important objectives is to determine the degree of optimality and safety for the load-bearing structures. This degree can be determined for both optimized and non-optimized objects. As the degree of cost optimality, we mean the approach of the design solution to a certain global minimum, at which the set of ratios of the actually acting strain-stress state factors in the structure sections to their limits is close to 1. Moreover, as the safety we mean mechanical safety. A system is mechanically safe if it has the required strength and rigidity during operation under normal conditions, as well as survivability (sustainability at progressive collapse) under emergency actions (mechanical local damages, impacts etc.).

To evaluate the degree of optimality of structural systems, it is advisable to have some simplified indicators, since with posterior unknown global minima according to one or another criterion for real objects; it is quite difficult to determine how optimal this structure will be. If the structure is newly designed, then genetic algorithms [1-3, 5], the particle swarm method, or combined exploratory strategies based on combined constraints satisfaction [6, 8, 9] can be used to obtain an optimal solution close to the global optimum. For reconstructed systems, for this purpose, one can use the algorithm [12].

In the formulation of the problem we are considering, margins of strength, stability and stiffness have a significant influence on the fault tolerance of load-bearing structures and therefore on the mechanical safety of the structural system as a whole. These margins are indirectly related to the risks of the consequences of the structural system failure in the event of an emergency, both during normal operation and under emergencies. It is advisable to evaluate the strength, stiffness and stability of the structure in a unified iterative procedure [6, 7, 9]. Design solutions with an increased level of mechanical safety can be obtained by conventional designing taking into account the survivability
condition in case of local damage, the use of confinement reinforcement \[ \text{[4, 7, 10, 11]} \] as well as by optimization taking into account the safety level \[ \text{[13, 14, 16-18]} \].

2. Methods

Let us introduce an integrated indicator of the total displacement margin of a structural system $\Delta \bar{\Delta} f$, which we will use as a measure of a quantitative assessment of the optimality of a deformable object with regard to ensuring mechanical safety. We define this indicator as follows:

$$
\Delta \bar{\Delta} f = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{f_{iv} - [f]_{v}}{[f]_{v}} + \frac{f_{ih} - [f]_{h}}{[f]_{h}} + \frac{f_{il} - [f]_{l}}{[f]_{l}} \right),
$$

where $f_{iv}, f_{ih}, f_{il}$ – vertical, horizontal deflections and longitudinal displacement of a node $i$ of the finite element model owing to external loads and impacts, respectively, $[f]_{v}, [f]_{h}, [f]_{l}$ – consequently are the permissible values of vertical, horizontal deflections, longitudinal displacements; $n$ is the number of nodes in the model. For normal operating conditions, the permissible deflections $[f]$ are determined by the requirements of the standards \[ \text{[19]} \] and design considerations, and in case of emergency actions by the requirements \[ \text{[20]} \] or other special conditions.

The next integrated indicator $\Delta \bar{\Delta} c$ is the total safety factor for the sections. For reinforced concrete structures, it can be defined as follows:

$$
\Delta \bar{\Delta} c = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{F_{i} - F_{ult}}{F_{ult}} \right),
$$

where $F_{i}$ – is the maximum design internal stress owing to external loads, $F_{ult}$ – is the limit force perceived by the section. For bending elements, the bending moment in the section $M_{i}$ is assumed as $F_{i}$, and the ultimate moment $M_{ult}$ is determined according to the standards \[ \text{[19]} \]. For steel structures, the indicator $\Delta \bar{\Delta} c$ is determined on the basis of the equivalent stress $\sigma_{e}$ according to the maximum-strain-energy theory (von Mises):

$$
\Delta \bar{\Delta} c = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{\sigma_{ei} - R_{y}}{R_{y}} \right),
$$

where $R_{y}$ – is the design bending resistance for steel.

The integrated indicator of the stability margin can be simplified based on this approach:

$$
\Delta \bar{\Delta} s = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{N_{i} - N_{cr}}{N_{cr}} \right),
$$

where $N_{i}$ – is the longitudinal force in the section, $N_{cr}$ – is the critical force according to Euler for a structural element.

It should be noted that the values of the permissible design values in formulas (1) - (4) must be used taking into account the parameters of the geometry and materials of structural elements. So, for example, for bending components of different spans, the values $[f]_{v}$ will be different. Thus, the indicator can estimate the degree of optimality at a minimum cost:

$$
\Delta \text{cost} = \Delta \bar{\Delta} f + \Delta \bar{\Delta} c + \Delta \bar{\Delta} s.
$$
The higher the value $\Delta_{\text{cost}}$, the less material is used for the structure, in an ideal theoretical case $\Delta_{\text{cost}} \to 3$. If $\Delta_{\text{cost}} \to 0$, material costs increase infinitely. To evaluate the safety of a design solution, taking into account the risk of losses in emergencies, you can use the following expression:

$$\Delta = \Delta_{\text{cost}} (1 - \frac{\xi}{\zeta}),$$

where $\xi$ is a value equal to the ratio of the cost of components destroyed by an emergency impact that do not ensure the survivability of the structural system to the total cost of the structure. If the value $\Delta \leq 0.1$, then the system is not safe and not optimal.

Analysis of the properties of optimal systems as well as a quantitative assessment of the level of their safety, made it possible to give the following design recommendations:

1. It is necessary to determine the need to ensure the survivability of the designed facility. If survivability is necessary to ensure, then you should go to points 2-7, if not, to points 3-5, 7.
2. Set the required safety level $\zeta$ for the structural system.
3. Formulate the constraints of the problem (conditions of strength, rigidity, stability, design and technological requirements). Generate discrete sets of variable parameters or construct functions that determine their values.
4. Find design parameters. It is advisable to choose sections of structural elements, parameters of reinforcement, shaping of structures for several variants of the object topology. At the same time, for a small number of variable parameters (3-5), it is recommended to use the methods of deterministic constrained optimization and with a larger number of them, methods of stochastic optimization, for example, the genetic algorithms.
5. Carry out manual design based on available practical experience. Perform checking calculation of the obtained solution in the FEA software package.
6. To assess the risks of material losses, if necessary, depending on the result, change the safety level and carry out step 4.
7. To assess the degree of optimality of the obtained variants of the design solution, expressions (1)-(6).

In the case of searching for solutions with several optimization criteria, it is necessary to solve the optimization problem for each criterion separately, then using the Pareto principle or the Nash equilibrium property to select the final solution [8].

3. Results
Let’s consider a reinforced concrete frame stack (Figure 1). The span of the stack is equal to the pitch and is equal to 12 m, the height is 6.0 m. The uniformly distributed load $q = 6.15$ kPa, distributed along the pitch to the main beams, was taken into account. Permissible deflection is $1200/250 = 4.8$ cm. The support anchors are rigid. The combination of dimensions and reinforcement for components is given in table 1.

| Size combination | Section dimensions, cm; Area of effective bar reinforcement, cm$^2$ | Size combination | Section dimensions, cm; Area of effective bar reinforcement, cm$^2$ |
|------------------|-------------------------------------------------|------------------|-------------------------------------------------|
| $T1$             | $h=12$, $b=8$, $A_s=2.36$                      | $T10$            | $h=36$, $b=21$, $A_s=24.13$                     |
| $T2$             | $h=14$, $b=9$, $A_s=3.39$                      | $T11$            | $h=39$, $b=24$, $A_s=24.13$                     |
| $T3$             | $h=17$, $b=11$, $A_s=4.62$                     | $T12$            | $h=48$, $b=26$, $A_s=24.13$                     |
| $T4$             | $h=18$, $b=12$, $A_s=6.03$                     | $T13$            | $h=53$, $b=32$, $A_s=24.13$                     |
| $T5$             | $h=23$, $b=15$, $A_s=7.63$                     | $T14$            | $h=66$, $b=35$, $A_s=30.54$                     |
| $T6$             | $h=23$, $b=17$, $A_s=9.41$                     | $T15$            | $h=72$, $b=44$, $A_s=30.54$                     |

15,
Let’s consider an evaluation of the optimality of design solutions for the following conditions:
- normal operation without taking into account the measures to prevent damage owing to the emergency column loss and without optimization (A);
- the same, but taking into account the optimization according to the criterion of the minimum of materials costs (B);

|   |  |  |  |
|---|---|---|---|
| T7 | 23 | 17 | 11.4 |
| T8 | 29 | 19 | 14.79 |
| T9 | 32 | 21 | 18.47 |

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- normal operation without taking into account the measures to prevent damage owing to the emergency column loss and without optimization (A);
- the same, but taking into account the optimization according to the criterion of the minimum of materials costs (B);

- optimization taking into account the normal operation and prevention of damage owing to the emergency actions by ensuring survivability (C);
- traditional design taking into account the considered emergency actions (D).

Let’s construct the reinforcements stress margin histogram for the scenario of eliminating supports for optimal design of the structure (Figure 2, a) and for traditional design (Figure 2, b). The results of calculating the integrated coefficients for design solution on figure 3 that make it possible to evaluate the degree of optimality of design solutions are given in Table 2.

**Figure 1.** Initial data and the result of solving the problem in case (B):
- a-c - initial data; d - profile numbers from table 1

- optimization taking into account the normal operation and prevention of damage owing to the emergency actions by ensuring survivability (C);
- traditional design taking into account the considered emergency actions (D).
Table 2. To assess the degree of optimality of a constructive solution

| Structure variant | Cost, rub | $\Delta\xi$, % | $\Delta\zeta$, % | $\Delta_{\text{cost}}$ | $\zeta$ | $\Delta$ |
|-------------------|-----------|----------------|----------------|------------------------|--------|---------|
| (A)               | 350,000   | 48             | 33             | 0,81                   | 0,714  | 0,231   |
| (B)               | 322,000   | 56             | 37             | 0,93                   | 0,714  | 0,265   |
| (C)               | 571,000   | 28             | 23             | 0,45                   | 0,047  | 0,428   |
| (D)               | 691,000   | 22             | 13             | 0,35                   | 0,047  | 0,333   |

Figure 2. Maximum stresses in reinforcement during the elimination of columns in the structure with optimal (C) and traditional design (D):
1 - columns A, C, G, J (Figure 1, a); 2 - columns D, F; 3 - column E, 4 - columns B, H; 5, 6 - columns B, H for scenario D
When analyzing design solutions, taking into account the beyond design effects, the phenomenon of buckling of columns was not recorded, and therefore indicator (4) is not taken into account in the table. Table 2 shows that the presented methods for evaluation of the optimality of a design solution allows choosing design solutions that are acceptable for the investor based on minimizing initial costs or ensuring the required ratio between the cost and safety of the structure. Here, the safest and most cost effective solution at this level of safety is solution (C). However, it does not have the highest cost. The most economical solution with regard to the initial cost only is solution (B), but it also has the least safety. The initial data for calculating the deflection safety factor $\Delta f\%$ shown on figure 4.

Figure 3. The result of solving the problem for cases C (a) and D (b)

Figure 4. An example of the initial data for calculating the deflection safety factor:
1 - data for an optimized system (B), 2 - usually designed structure (A)

4. Discussion
The specified indicators for calculating the degree of optimality and mechanical safety of reinforced concrete structures can be adapted for use of the other types of supporting systems. Formation of such indicators for other criteria of optimality associated, for example, with the environmental safety of structures, the comfort of the internal environment, etc. is a long-range objective.

5. Conclusion
Based on the results in studies relative to the properties of the stress-strain state of optimized reinforced concrete structures, a method is proposed for evaluation of the degree of optimality of a
design solution with regard to minimizing both initial costs and the level of risks of socio-economic losses in the event of emergencies. The proposed method makes it possible to evaluate the level of mechanical safety of a facility in the event of an emergency, as well as the necessity and scope of measures for reconstruction associated with increasing the load-bearing capacity of structural components.

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