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OPTIMIZATION OF BEARING STRUCTURES SUBJECT TO MECHANICAL SAFETY: AN EVOLUTIONARY APPROACH AND SOFTWARE

Anatoliy V. Alekseytsev [1], Al Ali Mohamad [2]

[1] Moscow State University of Civil Engineering (National Research University), Moscow, RUSSIA
[2] Technical University of Košice, Košice, SLOVAK REPUBLIC

Abstract. An approach to solving the urgent problem of optimizing the load-bearing structures of buildings and structures based on adapted genetic algorithms is presented. As a tool for finding a solution, iterative schemes are used, in which, in the classical approach to evolutionary modeling, a system of constraints is used that forms the operational requirements for reinforced concrete, steel and other structures. In this case, the value of the risk of material losses is used as one of the measures of the design optimality. This value is used to assess the feasibility of increasing the initial costs of manufacturing structures, taking into account the degree of their mechanical safety in case of emergency impacts. Groups of scenarios are considered as such impacts, including local damage to one or more load-bearing elements. A limitation is formed on the resistance to progressive collapse of the structure, which is interpreted as preventing large displacements and limiting deformations of certain parts or the structure as a whole. The magnitude of the risk is determined by a relative index determined as the ratio of the likely cost for damage from material loss to the initial cost of manufacturing the structure. The block diagrams that implement such iterative processes, information about the developed software and an example of optimization of the reinforced concrete supporting structure of the frame of an administrative multi-storey building are considered.

Keywords: genetic algorithms, evolutionary modeling, mechanical safety, optimization, progressive collapse, emergency actions, risk, software.

ОПТИМАЛЬНОЕ ПРОЕКТИРОВАНИЕ БЕЗОПАСНЫХ НЕСУЩИХ КОНСТРУКЦИЙ: ЭВОЛЮЦИОННЫЙ ПОДХОД И ПРОГРАММНОЕ ОБЕСПЕЧЕНИЕ

А.В. Алексейцев [1], Ал Али Мохамад [2]

[1] Национальный исследовательский Московский строительный университет, г. Москва, РОССИЯ
[2] Технический университет в Кошице, г. Кошице, СЛОВАКИЯ

Аннотация. Представлен возможный подход к решению актуальной задачи оптимизации конструктивных решений для несущих конструкций зданий и сооружений на основе адаптированных генетических алгоритмов. В качестве инструмента для поиска решения используются итерационные схемы, в которых при классическом подходе к эволюционному моделированию используется система ограничений, формирующая эксплуатационные требования к железобетонным, стальным и другим конструкциям. При этом в качестве одной из мер оптимальности конструкции используется величина риска материальных потерь. Эта величина используется для оценки целесообразности увеличения первоначальных затрат на изготовление конструкций с учетом степени их механической безопасности при запроектных воздействиях. Рассматриваются группы сценариев, включающие локальные повреждения одного или нескольких несущих элементов. При этом ставится ограничение на живучесть конструкции, которая трактуется как недопущение больших перемещений и предельных деформаций определенных частей или конструкции в целом. Величина риска определяется относительным индексом, определяемым соотношением вероятного ущерба от материальных потерь в стоимостном выражении к первоначальным затратам на изготовление конструкции. Рассматриваются блок-схемы, реализующие такие итерационные процессы, сведения о разработанном программном обеспечении и пример оптимизации железобетонной несущей конструкции каркаса административного многоэтажного здания.

Ключевые слова: генетические алгоритмы, эволюционное моделирование, механическая безопасность, оптимизация, живучесть, запроектные воздействия, риск, программное обеспечение.

INTRODUCTION

The problem of optimizing reinforced concrete and steel frames considering their safety level is mostly understudied. There are only a few studies that concern particular aspects of the problem to a different extent [1-4]. At the same time, some studies focus on both mechanical and technogenic safety [5]. As an example of optimizing, let's consider relatively simple objects, while hazards shall be excluded from a single iterative procedure. Structures safety is considered according to the values loss risk factor calculation [6-7]. In this regard, it may be difficult to optimise a design solution, considering costs of construction site life cycle stages in its in normal operations and considering its resistance to beyond design basis effects. Recent search schemes based on modern information technologies allows for getting better in solving this problem. Firstly, these are genetic algorithms [8-10], particle swarm methods [11-13], ant colony [14], and firefly's methods [15]. These algorithms may get accustomed to solving optimisation tasks both reinforced concrete, steel and other structures of various types. The article is concerned with the common approach to optimisation of reinforced concrete and steel load bearing structures considering the level of their mechanical safety, as well as evolutionary algorithms implementation for truss and plated and truss structures. It is proposed to introduce a measure of relative integral socio-economic losses risk as an estimate of safety level. The risk considers both normal operations of structural systems as part of a functional ongoing process in the building and emergency conditions related to mechanic damage of individual units or elements.

1. THE PROBLEM FORMULATION

As an optimal design goal, we'll use minimization of value terms of materials consumption of a structure, the labour intensity involved in its manufacture, and also safety level at emergency.

$$C(\{Y\}) \to \min ;$$
$$\{Y\} = \left\{\{y\}_1, \{y\}_2, ..., \{y\}_{Np}\right\}, \tag{1}$$

where C is a notional value (conventional units), that considers the materials that make up the load bearing structure, manufacturing features and socio-economic losses risks; $\{Y\}$ is a set of design parameters that vary in search process, consisting of N_p disjoint subsets $\{y\}_{it}$, $it = (1, ..., N_p)$; $\{y\}_{it}$ – a set of parameters consisting of parameter values admitted for selection in search process, corresponding to its *it* type.

This parameter type implies, for example, combinations of building element cross sections, position of structural joints, material classes of which it is made, plate width and etc. Expressions for calculation of the value C for specific cases of structure optimisation have various notations, for example, for reinforced concrete frames [16]:

$$C = (P_c + P_r + P_f) \to P_{\min}, \tag{2}$$

where P_c, P_r, P_f – prime cost of materials and manufacture for concrete, fittings, casing and associated materials, respectively, $P_{\min}$ – some small real number;

– for steel frames [17]:

$$M = \rho \sum_{i=1}^{n} A_i l_i \to \min, \tag{3}$$

where ρ is steel density, A_i, l_i are area and length of structure element, respectively, and n *is* their number;

– for wood structures [18]:

$$f(\vec{X}) = \frac{C_{tim}V_{tim}(\vec{X}) + C_{pl}V_{pl}(\vec{X})}{a_n b_n} \to \min, \quad (4)$$

where $(\vec{X})$ is a vector of variables; $V_{tim}(\vec{X})$, $V_{pl}(\vec{X})$ are wood and plywood volumes in the fabricated structure; a_n, b_n are bay and width of a wood structure; C_{tim}, C_{pl} are weight coefficients for wood and plywood.

In solving the minimisation problem (1) by way of task (2) and (4), socio-economic losses risks is not considered in the goal function, that significantly diminishes the mechanical safety level of such optimized structures. The goal function is proposed as follows:

$$C = \left(C_s + R_s\right) \to \min,$$
$$R_s = \sum_{i=1}^{N}\sum_{j=1}^{M} p_{i,j}U_{i,j}, \quad (5)$$

C_s is a value related to costs for materials, structure fabrication, joint connection arrangement and etc.; R_s is the value terms of socio-economic losses risk defined by the probability $p_{i,j}$ for emergency *j* at stage *i* of structure life cycle. This probability can be determined based on the well-known Bayes' formula for conditional probability, *N, M* are a number of emergencies considered in optimisation for life cycle stages and those that may occur at this stage.

In solving load bearing structures optimisation problems, the following main active constraints are used:

– structure elements strength. This criterion can be expressed in strains, deformations and critical forces in dangerous cross section of a building element. These factors should not exceed the set design resistances, deformations, and forces;

– structure stiffness along linear displacements or angles of rotation;

– stability of system geometrical shape in the presence of its structural (topological) changes.

Passive constraints may be presented by conditions for ensuring structure overall stability, local durability of its structural elements, observing the requirements for unification of constructive solution, manufacturing or assembling processes.

It's obvious that the growing complexity of design solutions creates the necessity of varying dozens of design parameters. In this regard, manual approaches to optimisation become unacceptable, while gradient-based optimization algorithms are not efficient. With that said, methods evolve based on a combination of search algorithms, linear and non-linear mathematical programming. The major problem in implementation of such an optimisation approach for load bearing structures lies in the necessity of multiple automatic calculation at structure strain-stress distribution. Let us consider one of the variant for this calculation arrangement.

2. GENERAL SOLUTION SEARCH CIRCUIT

A number of basic stages is proposed for evolutionary algorithm implementation in terms of design solution.

2.1. Defining one or several optimisation criteria corresponding to problem solution goal. For example, cost minimum, ensuring strength, collapse resistance in emergency and etc. Here a decision is also taken about optimisation task decomposing, its phasing for a purpose of optimal topological synthesis, search for rational form. An example of such decomposition is addressed in work [19].

2.2. Formation of data on structure computational model, design parameter sets, force, kinematical, structural and technological constraints of the task.

2.3 Development or selection of a mathematical model for estimation of constraint satisfaction. A proven calculation model can be used for bearing structures set forth in regulatory documents, and also computing model based on finite elements method. Moreover, for evolutionary approach implementation there is a problem for solver integration into the iterative search scheme. One of such methods will be stated in this paper.

2.4 Verification of constraint satisfaction, calculation of target function values and implementation of preserving the best solution for further reproduction and improvement of decisions. In using several optimality criteria, the target function value can be calculated based on weight coefficients x_k per each of the criteria:

$$C = \sum_{k=1}^{Nc} C_k x_k, \ \sum_k x_k = 1, \quad (6)$$

where C_k is a goal function value upon criterion k, Nc is a number of criteria.

2.5 Verification of the condition of search process end. Provided that the condition for ending the iterations is satisfied the search is stopped. If it's not, then based on existing best solutions, structure options are modified by way of changing some varied parameters and proceeding to stage 2.4.

Some integral iteration number N_p is considered as a criterion of ending the iterations for genetic search during which no improvements occur in the iteration process:

$$N_p = {}^{n/3}\sqrt{mn!}, \quad (7)$$

where n is a number of independently varied parameters; m is the arithmetic mean for values admitted for each parameter selection. Implementing the condition for ending the iterations is shown in Fig. 1.

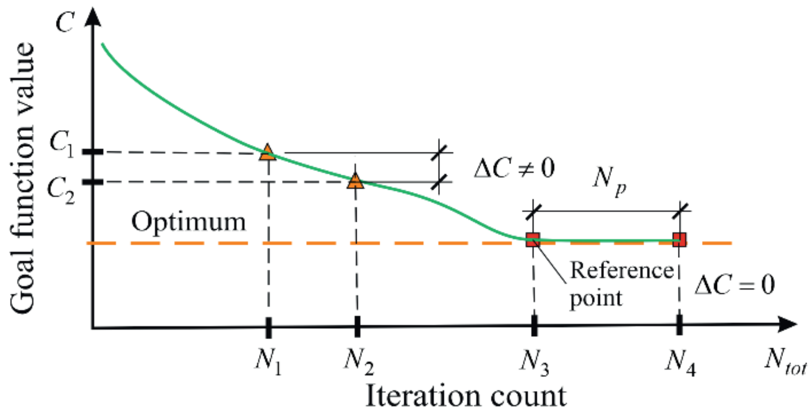

Figure 1. For realisation of iteration stopping criterion

Upon completion of iteration stopping, a decision obtained as a result of search is verified for satisfaction of passive (not considered during the iteration process) constraints.

Such constrains may include local durability of joint connection elements, design features related to ensuring structural support, local plate durability, ensuring necessary installation conditions and etc. Studies [20-23] explain in more detail the evolutionary algorithm in respect to individual types of load bearing building constructions. We'll demonstrate the content of stage 2.2 and stage 2.4 of evolutionary approach using the example of reinforced concrete simple beam (figures 2, 3). In this case, 4 parameters vary independently: higher and lower fitting diameters, concrete and fitting class. Some parameters may remain permanent.

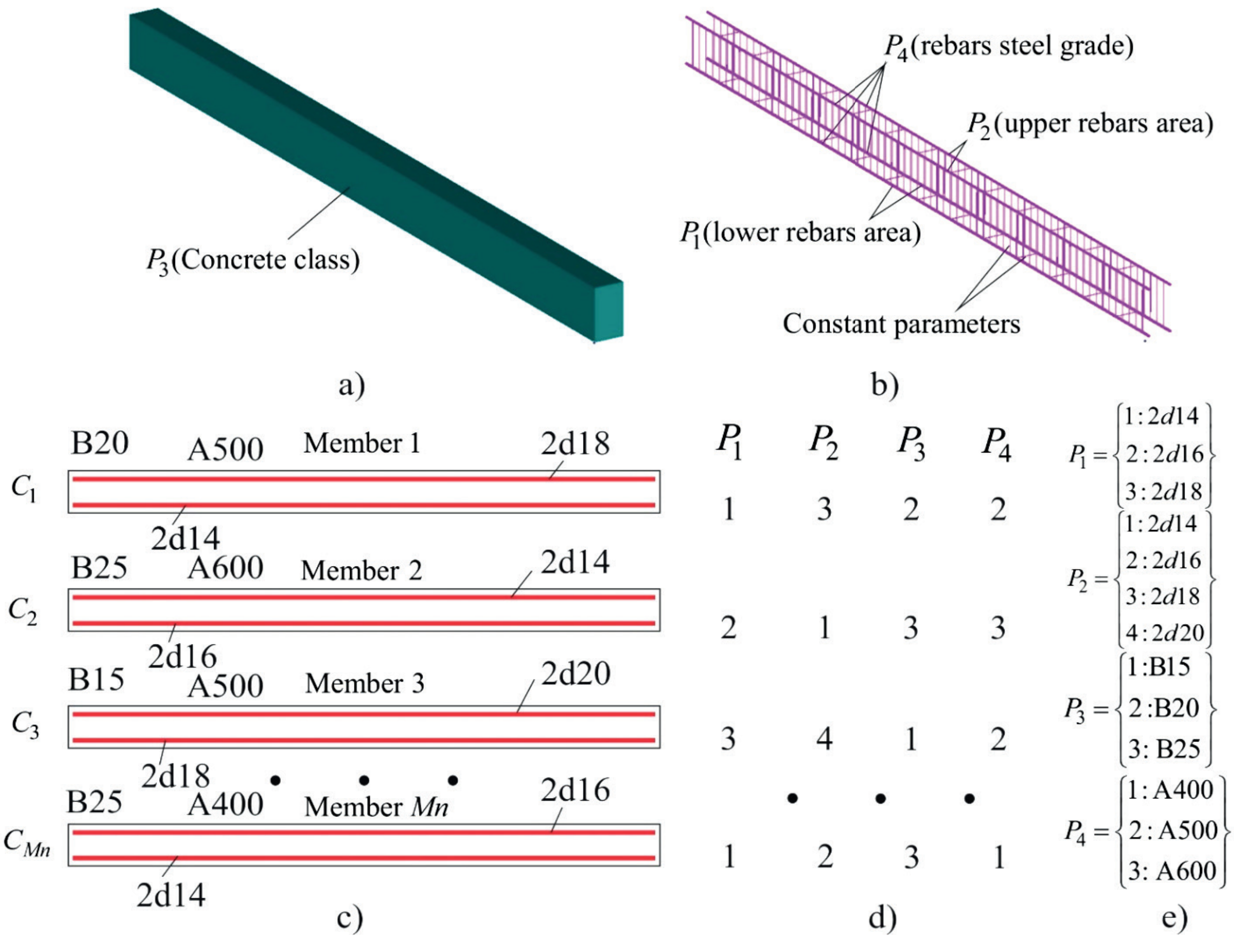

Figure 2. Presentation of reinforced concrete beam and sets of such structures in evolutionary approach: examples of setting varying and non-varying parameters (a), (b), vision of initial occasionally generated decision set (c), example of coding parameter values (d), set of permitted parameter values (e)

The choice of structure members for further solution improvement is made based on roulette-wheel selection method in fig. 3, a, where the choice probability is determined by the value:

$$l_i = f_i \Big/ \sum_{j=1}^{N} f_j \,,\, f_i = 1\Big/ C_i^I \,, I = 1..4 \,, \tag{8}$$

Structure modification is made based on operators, examples of which are shown in fig. 3, b, c. In making a decision about preservation of the best solution the following elitism EC criteria are used (fig. 3d):

$$\begin{cases} (\forall A_i \in \Pi_A) \exists A_i \notin \Pi_B \\ C(\forall A_i \in \Pi_A) \le C_{\max}(\tilde{A}_{\tilde{i}} \in \Pi_B) \end{cases} \Rightarrow , \\ \Rightarrow \left(\tilde{A}_{\tilde{i}} \in \Pi_B\right) = \left(A_i \in \Pi_A\right). \tag{9}$$

The first condition in the system means absence in elite set Π_B a copy from the set Π_A, and second condition means that the meaning of a target criteria for a member from set Π_A must be less than maximum from the elite set. It should be noted that dimensions M_n of a current set and M_{ne} elite set of decisions may differ. Practical use of evolutionary approach showed that $M_n \in [15 \div 50]$, $M_{ne} \in [10 \div 25]$.

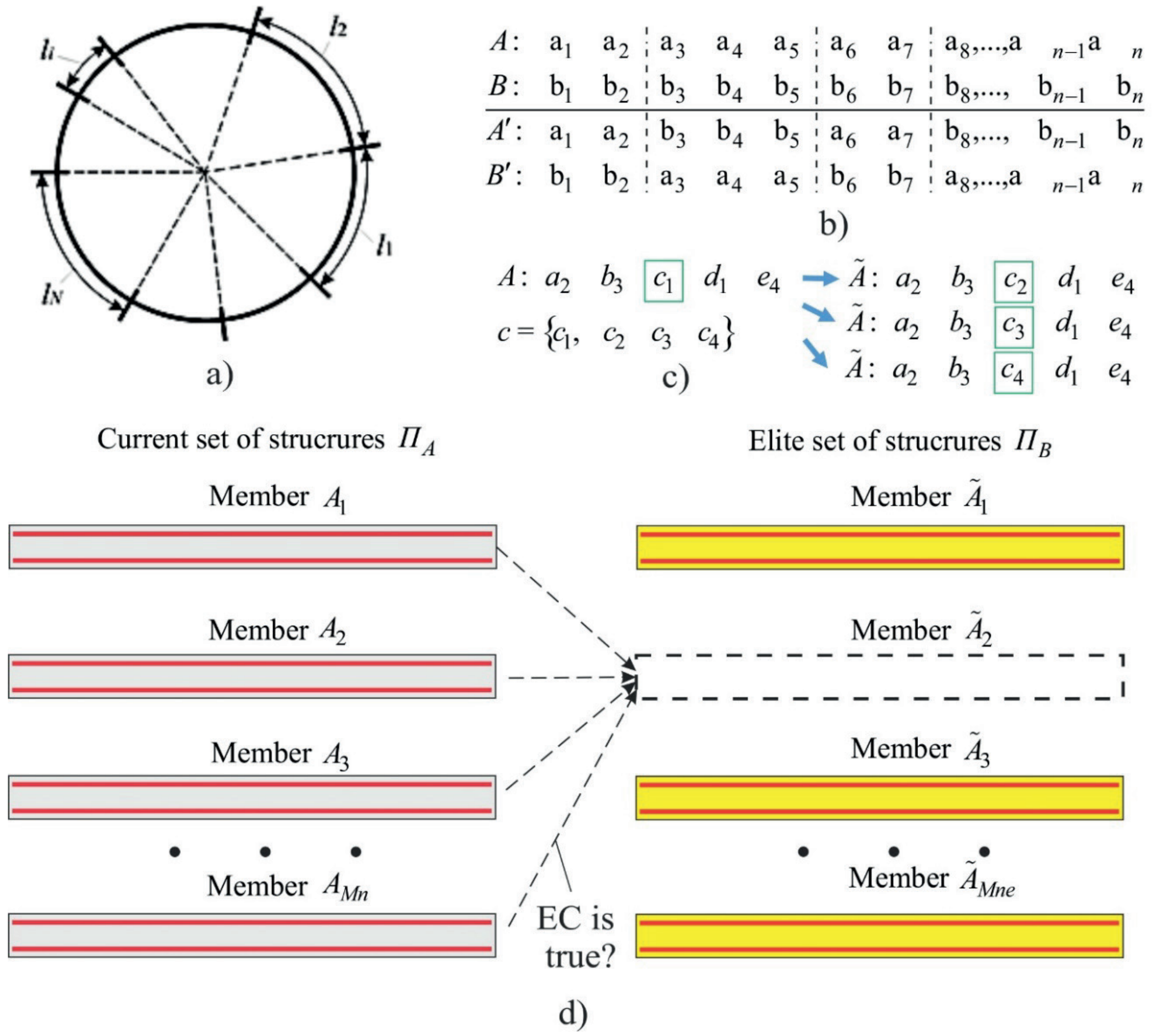

Figure 3. Evolutionary search components: roulette-wheel scheme (a), multipoint crossingover (b) and mutation (c) operators, elite population editing scheme on the basis of elitism criteria (EC) satisfaction

3. INTERACTION WITH PROGRAM COMPEX SOLVERS

Current requirements to structural designing assume the assessment of their strain-stress distribution taking into account physical, geometrical and constructive nonlinearity. It calls for using modern program complexes with a possibility of exchanging data with a solver and exterior programme developments. Simcenter “Femap”. Preprocessor of this complex can integrate with all modern solvers, while we’ve used NX Nastran solver. The scheme of organisation of evolutionary search program interaction [24, 25] with Simcenter “Femap” is shown in fig. 4.

The operating system is used to exchange data between the finite element complex solver and the genetic search program. This is possible if there is an open format for the input / output file, as well as the ability to run the solver without using special pre / postprocessor commands.

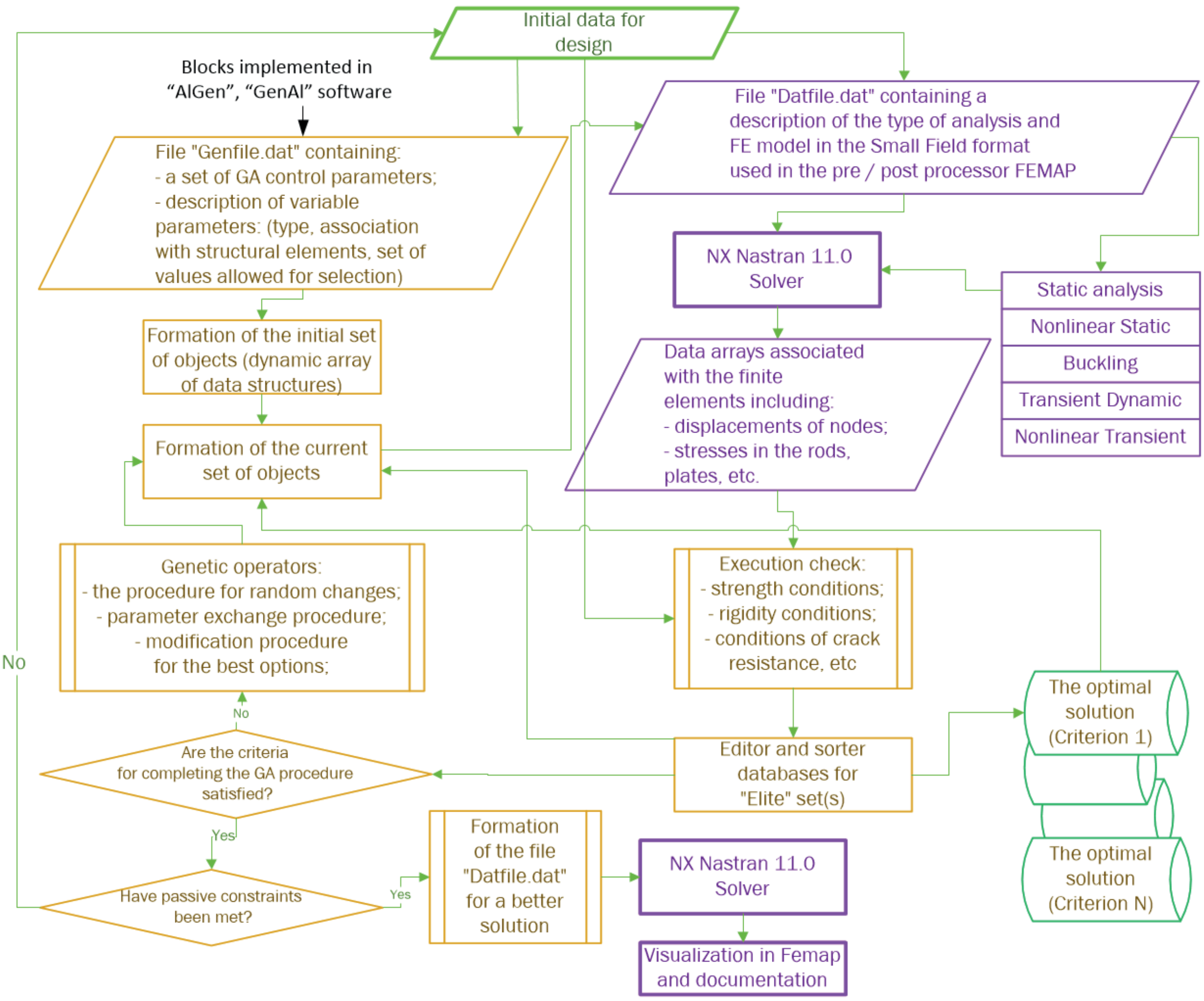

Figure 4. Structure of software employing the evolutionary process search for bearing structure optimization

4. EXAMPLE OF USING EVOLUTIONARY ALGORITHM IN VARIOUS APPROACHES TO DESIGNING

Let us consider the designing of the frame of half precast multi-storey civil building. Frame ceilings and finishes are precast. It is believed, that their parameters to be non-variable. It means, that they are not considered within the search.

There are three options of frame designing to be considered:

– using solutions given in typical design documentation (s. B1.020) allowing for normal operations (I);

– using evolutionary search with no regard for safety limits according to presentation (5) in $R_S = 0$ (II);

– using evolutionary algorithm in accordance with presentation with a possibility of considering emergencies $R_S \neq 0$ while ensuring mechanical safety at level $\zeta = R_S / C_S = 0.2$. Frame calculation scheme is shown in fig. 5, a. As an emergency script, it is offered to have an opportunity of excluding their design diagram one from columns K1-K7 as a result of local mechanical damage fig. 5, b.

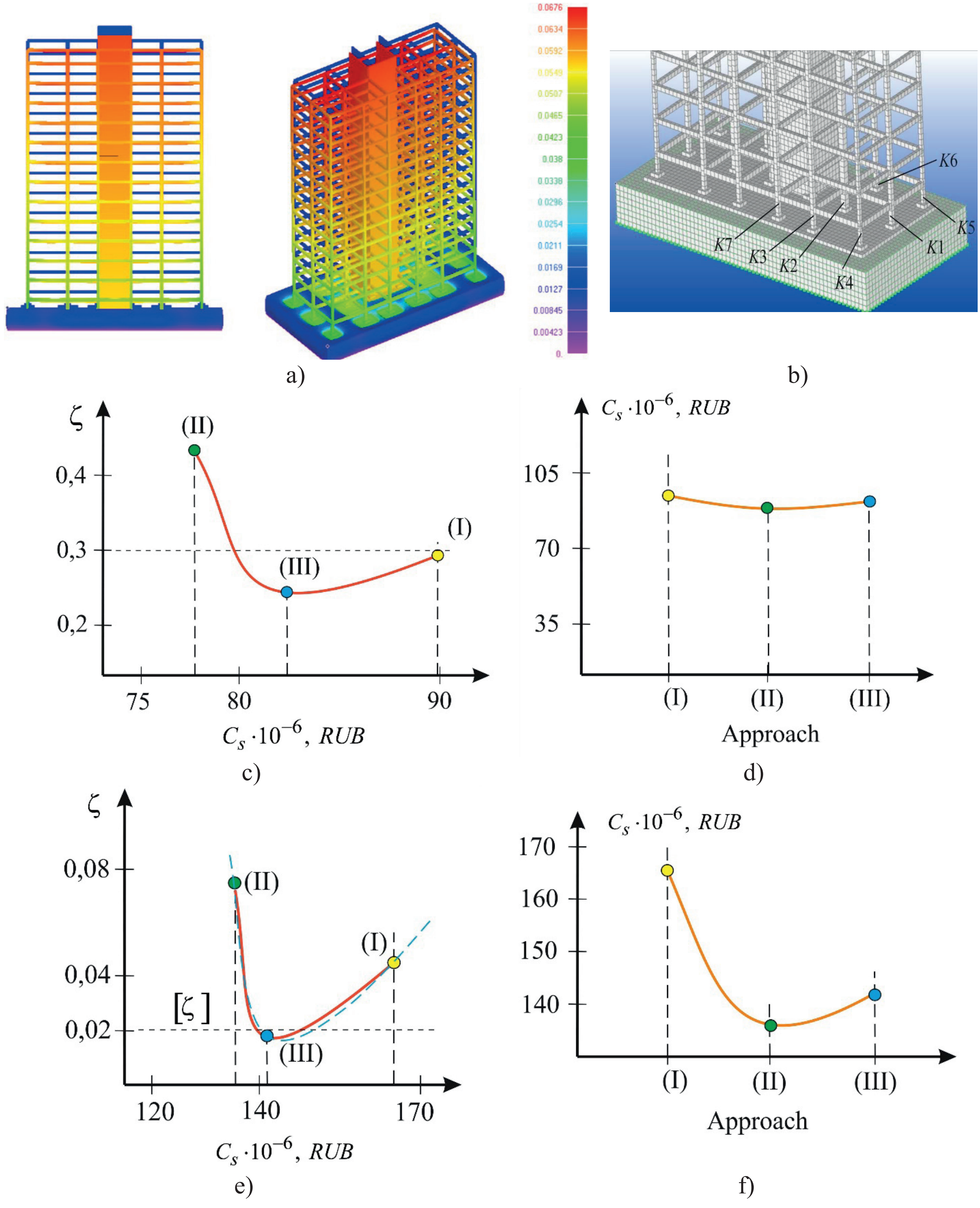

Figure 5. Results of building frame designing: design diagram including the map of vertical yield of the building foundation (a), emergency scripts (b), results of safety and cost estimation in normal operations (c, d) and emergency (e, f)

As the figure 5, c, d shows, in normal operations regardless of possible emergency conditions, the approach to designing according to rules (I) allows for gaining the structure value comparable to optimisation algorithms (II), (III). Moreover, structure cost-cutting using (II) approach significantly decreases its safety. Using constrains in view of the risks in optimisation algorithms (III), a 40% safer structure option has been obtained with very insignificant appreciation (to 10%) in comparison to approach (I).

DISCUSSION

Considering emergency condition scripts, conventional approach (I) does not allow for obtaining minimal design cost in reaching a relative level risk $\zeta \leq 0.2$. Utilising genetic search (II) in minimal cost may appear unacceptable due to a low safety level, which appeared to be almost 2 times lower than in approach (I). Approach (III) is the most cost-saving solution in constraints to safety level.

CONCLUSION

1. An approach has been developed to bearing structure parameter optimisation based on evolutionary algorithm.
2. Solving the problems of optimizing building load bearing structures of normal and advanced responsibility level must include a requirement for considering the risk of consequences from an accident.
3. A scheme of interaction of evolutionary search iteration procedure with modern program complexes.

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Anatoly V. Alekseytsev, docent, candidate of technical sciences, associated professor of the department "Reinforced concrete and stone structures"; National Research Moscow State Technical University (NRU MGSU), Russia, Moscow, Yaroslavskoe sh., 26, Scopus ID: 57191530761, Researcher ID: I-3663-2017, ORCID: 0000-0002-4765-5819, tel .: +7 (495) 287-49-14. E-mail: alekseytsevav@mail.ru.

Al Ali Mohamad, Ph.D. tech. Sci., Head of the Department of Steel and Wooden Structures, Technical University of Kosice, Slovakia, Researcher ID: AAH-5275-2019, Scopus ID: 55516059900. ORCID:0000-0001-7866-8156. Letná 9 042 00 Košice Slovak Republic E-mail: alali@tuke.sk

Алексейцев Анатолий Викторович, доцент, кандидат технических наук, доцент кафедры «Железобетонные и каменные конструкции»; Национальный исследовательский московский государственный технический университет (НИУ МГСУ), Россия, г. Москва, Ярославское ш., 26, Scopus ID: 57191530761, Researcher ID: I-3663-2017, ORCID: 0000-0002-4765-5819, тел.: +7(495)287-49-14. E-mail: alekseytsevav@mail.ru.

Ал Али Мохамад, канд. техн. наук., заведующий кафедрой «Стальные и деревянные конструкции», Технический университет г. Кошице, Словакия, Researcher ID: AAH-5275-2019, Scopus ID: 55516059900. ORCID:0000-0001-7866-8156. Letná 9 042 00 Košice Slovak Republic. E-mail: alali@tuke.sk