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An algorithm for minimizing material consumption in steel frames considering local failures of their individual elements

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This article introduces an innovative algorithm designed for optimizing steel frames by incorporating considerations of local failures in their elements. The primary objective of the proposed algorithm is to enhance both structural reliability and economic efficiency. It achieves this by calculating the minimum weight of structural components while ensuring that its reliability remains intact. This approach is particularly significant as it accounts for various conditions throughout the lifecycle of the structure, including normal operating conditions and potentially hazardous situations arising from structure elements failures. By systematically evaluating these factors, the algorithm aims to provide engineers with a robust tool for designing safer and more efficient steel frame structures, contributing to improved performance and durability in the face of unforeseen challenges.

Keywords: elements failures, steel frames, structure optimisation, reliability, innovative algorithm.

Абдуллах Х., Алехин В. Н.
Алгоритм минимизации расхода материала в стальных каркасах с учетом локальных разрушений их отдельных элементов

Данная статья представляет инновационный алгоритм, разработанный для оптимизации стальных рам с учетом локальных отказов их элементов. Основная цель предлагаемого алгоритма — повысить надежность конструкции и экономическую эффективность. Это достигается путем вычисления минимальной массы элементов при сохранении их надежности. Такой подход особенно важен, поскольку учитывает различные условия эксплуатации конструкции, включая нормальные рабочие состояния и потенциально опасные ситуации, связанные с отказом элементов. Алгоритм предоставляет инженерам инструмент для проектирования более безопасных и эффективных стальных рам, повышая их долговечность и устойчивость к непредвиденным ситуациям.

Ключевые слова: разрушение элементов, стальные рамы, оптимизация конструкции, надежность, инновационный алгоритм.

Introduction

In modern construction projects, steel frames play a key role due to their high strength and design flexibility [2]. Optimizing the parameters of steel frames is an important task aimed at reducing material costs and increasing economic efficiency without compromising the safety and reliability of the structures. One of the main indicators of cost-effectiveness in steel-bearing frames is their minimum mass.

However, the optimization process of steel frames elements becomes significantly more complex when considering the possibility of local failures-loss of load-bearing capacity in structural elements, which can lead to progressive collapse of the entire structural system. Such failures are strictly prohibited by current anti-collapse design codes[1] [11; 13]. In these scenarios, the redistribution of loads to other components within the frame must be carefully considered during the calculation process to ensure structural safety and compliance with design standards [5–9].

Traditional calculation methods do not provide for monitoring material reserves that added to enhance the reliability of the structure under such scenarios, leading to material overconsumption [1].

While previous studies, such as [3; 4; 10], focus on enhancing the economic efficiency of steel frames under progressive collapse scenarios by incorporating probabilistic models of accidental event occurrence, this study takes a different approach. It directly optimizes material consumption of structural elements without considering their individual failure probabilities, instead assuming a uniform failure probability across all frame elements. This simplification is justified by the significant uncertainties surrounding accidental loads and events [12].

1 СП 385.1325800.2018 Защита зданий и сооружений от прогрессирующего обрушения. Правила проектирования. Основные положения. М.: Минстрой России, 2018.

This objective was achieved by developing an algorithm designed to minimizes the material reserves of steel frames under conditions of potential local failures in their elements. The algorithm simulates various damage scenarios and calculates load redistribution, determining the minimum cross-sectional masses of the frame elements. This approach allows for a reduction in excessive steel reserves while maintaining the reliability of the structure in the event of loss of load-bearing capacity in individual parts.

Methodology

Optimization problem formulation:

$$\Delta M = \sum_{i=1}^{c} \Delta m_i \left(X_1, X_2,.., X_p\right) +$$

$$+\sum_{i=1}^{b} \Delta n_i \left(X_1, X_2,.., X_t\right) \to \min; \qquad (1)$$

subject to the constraints:
$l_a \le X_a \le u_a$, for a $= 1, 2, ..., E_c$;
$g_d\left(X\right) \le y_d$, for d $= 1, 2, ..., I_c$,
where ΔM — is the difference in mass of the whole structure before and after local failure; $\Delta m_i \left(\Delta n_i\right)$ — is the difference in mass of the i column (beam) of the frame before and after local failure; $X_p \left(X_t\right)$ — is the number of adjustable parameters for the cross-sectional dimensions of frame columns (beams); c — is the number of frame columns; b — is the number of frame beams; E_c — is the number of explicit constraints corresponding to the number of adjustable parameters of the frame elements (these constraints set the upper (u_a) and lower (l_a) bounds for each parameter in the optimization process); I_c — is the number of implicit constraints $\left(g_d\left(X\right)\right)$, which include the conditions ensuring load-bearing capacity and stiffness.

The formulated optimization problem for the frame, in the general case, is a nonlinear integer programming problem, since both the objective function and the constraints are nonlinear, and the values of the sought parameters can be selected from a discrete integer set [2].

To address this optimization problem, a structured algorithm was developed. The following block diagrams illustrate the workflow and decision-making process within the algorithm. The first diagram (Figure 1) presents an overview of the main stages in the algorithm, including the initialization, setup, and selection of minimum cross-sections for structural elements.

First, the algorithm is designed to determine the minimum masses of structural elements under normal operating conditions, without considering the loss of load-bearing capacity of any frame element.

After this, the main part of the algorithm begins, which is designed to search for the minimum masses of the frame elements under special emergency conditions, where the loss of load-bearing capacity of a frame element is assumed.

The second diagram (Figure 2) goes into more detail, outlining the iterative steps taken to calculate the objective function, adjust parameters, and verify convergence.

As a convergence condition for the solution, the algorithm employs two criteria to ensure stability:

— Threshold for total mass change: The optimization process considered complete if the difference in total material mass between successive iterations falls below a specified threshold. This signifies, that further iterations would result in only negligible improvements in mass minimization, indicating global stability of the frame.

$$\Delta M = \frac{M_{t-1} - M_t}{M_{t-1}} \le \varepsilon_M, \qquad (2)$$

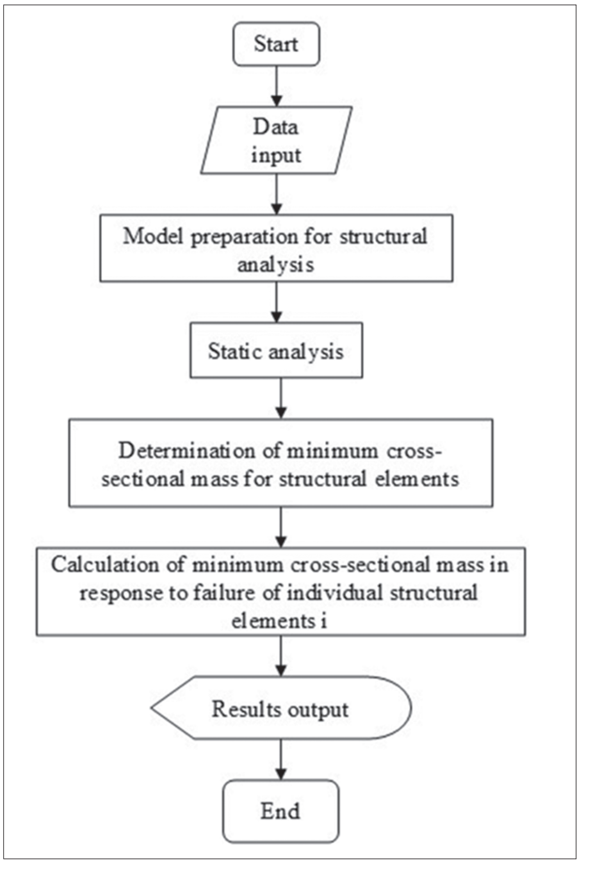


Figure 1. Consolidated block diagram of the algorithm.
Author H. Abdullah

where M_t is the total material mass for the whole structure elements in the current iteration; M_{t-1} is the total material mass for the whole structure elements in the previous iteration; ε_M is a small, predefined value.

— Standard deviation of mass change among elements: The standard deviation of mass changes for individual elements is monitored to assess local stability. If this standard deviation is below a specified threshold, it indicates that the mass adjustments are consistent across all elements, meaning there are no significant variations in mass changes from one element to another.

$$\sigma_{\Delta mi} \le \varepsilon_\sigma, \qquad (3)$$

where $\sigma_{\Delta mi}$ is standard deviation of mass change for frame elements; ε_σ is a small, predefined value.

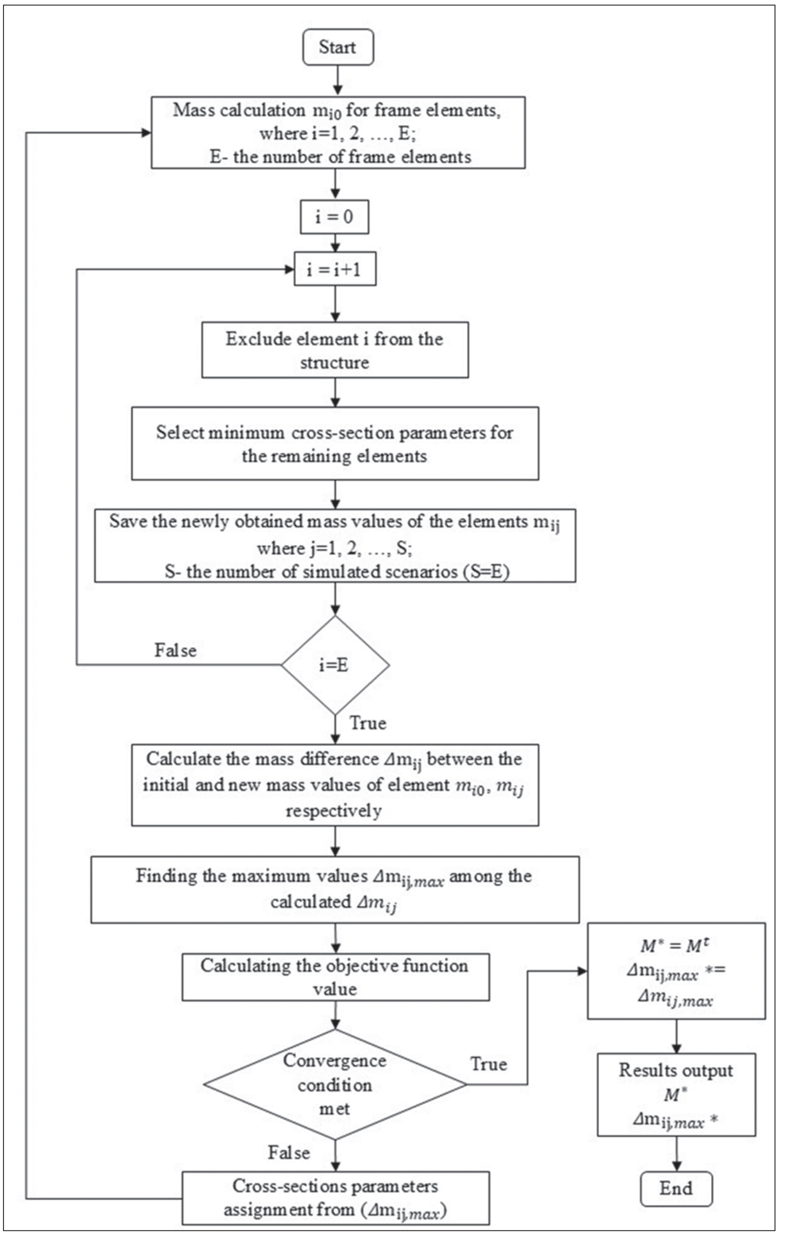
This approach ensures that, while the overall mass is close to converging, individual elements are not fluctuating too much from one iteration to the next.

In this study, the algorithm is designed to analyse welded I-shaped steel cross-sections, which are characterized by 4 adjustable parameters, denoted as $X_p = X_t = 4$ (Figure 3).

Where X_1 — web height (h_w), X_2 — web thickness (t_w), X_3 — flange thickness (t_f), X_4 — flange width (b_f).

The design process will adhere to the constraints and specifications outlined in the Russian code for steel structures[2]. Compliance with the code‘s requirements, including load combinations, material properties, and safety factors, will be ensured throughout the analysis and optimization of cross-sections. The algorithm will incorporate these regulatory standards to validate the structural integrity and performance of the designed sections.

2 СП 16.13330.2017 Стальные конструкции. Актуализированная редакция СНиП II-23-81*. М.: Минстрой России, 2017.



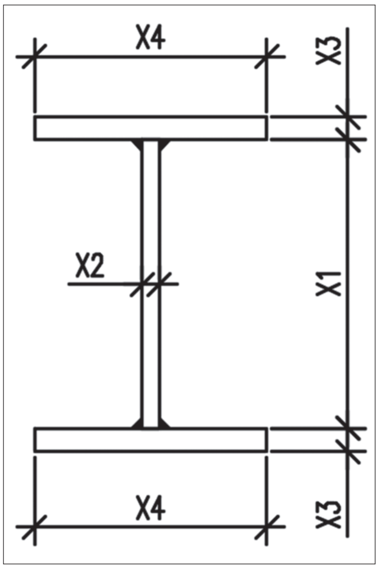


Figure 3. Optimized Parameters of I-Shaped Cross-Section. Author H. Abdullah

Figure 2. Block diagram of the algorithm for finding the minimum of the objective function. Author H. Abdullah

For structural members experiencing axial forces, whether in tension or compression, the strength condition is defined as follows:

$$\left(\frac{N}{A_n \cdot R_y \cdot \gamma_c}\right)^n + \frac{M_x}{C_x \cdot W_x \cdot R_y \cdot \gamma_c} + \\ + \frac{M_y}{C_y \cdot W_y \cdot R_y \cdot \gamma_c} \le 1, \quad (4)$$

where:
N, M_x, M_y — are the absolute values of the axial force and bending moments, respectively, under the most unfavourable combination of these forces;
A_n — net cross-sectional area;
W_x, W_y — moments of resistance of the cross section relative to the x-x and y-y axes, respectively;
R_y — design resistance of steel to tension, compression, and bending based on the yield strength;
γ_c — service conditions factor;
n, C_x, C_y — coefficients adopted in accordance with (СП 16.13330.2017).

For members subjected to shear forces, the strength condition is:

$$\frac{Q \cdot S}{I \cdot t_w \cdot R_s \cdot \gamma_c} \le 1, \quad (5)$$

where:
Q — shear force;
S — static moment of the gross sheared portion of the cross-section relative to the neutral axis;
I — moment of inertia of the gross cross-section
R_s — design shear resistance of steel.

Stability constraint for centrally compressed members subjected to compression and bending in two principal planes:

$$\frac{N}{\varphi_{exy} \cdot A \cdot Ry \cdot \gamma_c}, \quad (6)$$

where φ_{exy} — coefficient adopted in accordance with (СП 16.13330.2017).

Constraints related to local buckling of the web in compression, bending, and combined compression-bending members:

$$\overline{\lambda_w} = \frac{h_{ef}}{t_w} \cdot \sqrt{\frac{R_y}{E}} \leq \overline{\lambda_{uw}} . \quad (7)$$

Also, for the element flange:

$$\overline{\lambda_f} = \frac{b_{ef}}{t_f} \cdot \sqrt{\frac{R_y}{E}} \leq \overline{\lambda_{uf}} , \quad (8)$$

where:

$\overline{\lambda_w}, \overline{\lambda_f}$ — effective slenderness ratio of the web and flange;
h_{ef}, b_{ef} — design height of the web and flange width;

$\overline{\lambda_{uw}}, \overline{\lambda_{uf}}$ — limiting effective slenderness ratio of the web and flange.

Limitation based on the maximum beam deflection:

$$f \leq [f], \quad (9)$$

f — beam deflection;
$[f]$ — allowable beam deflection.
constraint on the maximum allowable height of the cross-section:

$$h_w + 2 \cdot t_f \leq h_{\max}; \quad (10)$$

design constraints:

$$t_f \geq t_w; \quad (11)$$

constraints due to technological requirements (weldability of elements):

$$3t_w \geq t_f . \quad (12)$$

Expected results

The algorithm should provide an optimized set of cross-sectional dimensions for each structural element that meets load-bearing and safety requirements. These optimized dimensions are expected to minimize redundancy, allowing for the most effective use of materials.

Also, by modelling scenarios with localized failures, the optimized design should demonstrate robustness, with the ability to redistribute loads effectively in the event of partial element failure. This will enhance the overall resilience of the structure, ensuring it maintains load-bearing capacity under such conditions.

Conclusions

This study has presented an innovative approach for optimizing the structural design of steel frames by considering the potential for local failures in individual elements. The proposed algorithm identifies the optimal cross-sectional properties to minimize material use while maintaining structural integrity, even in the event of an element's loss of load-bearing capacity. The expected results demonstrate that this method could effectively reduce material usage without compromising safety of the structure.

Future work will involve implementing the developed algorithms in Python within the ANSYS environment to automate and streamline the process. This integration will facilitate obtaining results directly within a powerful analysis tool, enhancing practical applications for structural engineers. This step will allow for more efficient and accessible optimization processes in real-world scenarios.

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