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

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Abstract. 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.

1 Introduction

In modern construction projects, steel frames play a key role due to their high strength and design flexibility [1]. 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 becomes 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. In such situations, the load redistributed to other elements of the frame, necessitating this redistribution to be accounted for in calculations [2-6].

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.

To address this issue, an algorithm developed that 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.

2 Methodology

Optimization problem formulation:

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

subject to the constraints

$$l_a \leq X_a \leq u_a, \text{for a} = 1, 2, \dots, E_c;$$
$$g_d(X) \leq y_d, \text{for } d = 1, 2, \dots, I_c,$$

where c – is the number of frame columns; $\Delta m_i(\Delta n_i)$ – is the difference in mass of the i column (beam) of the frame before and after local failure; X_p – is the number of adjustable parameters for the cross-sectional dimensions of frame elements; 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 and lower bounds for each parameter in the optimization process); I_c – is the number of implicit constraints, which include the conditions ensuring load-bearing capacity and stiffness.

To address the formulated 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.

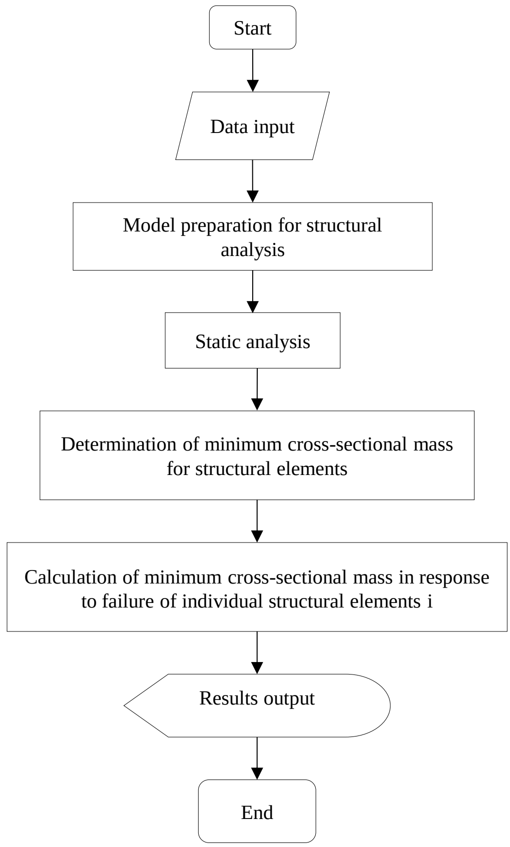

Fig.1. Consolidated block diagram of the algorithm.

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

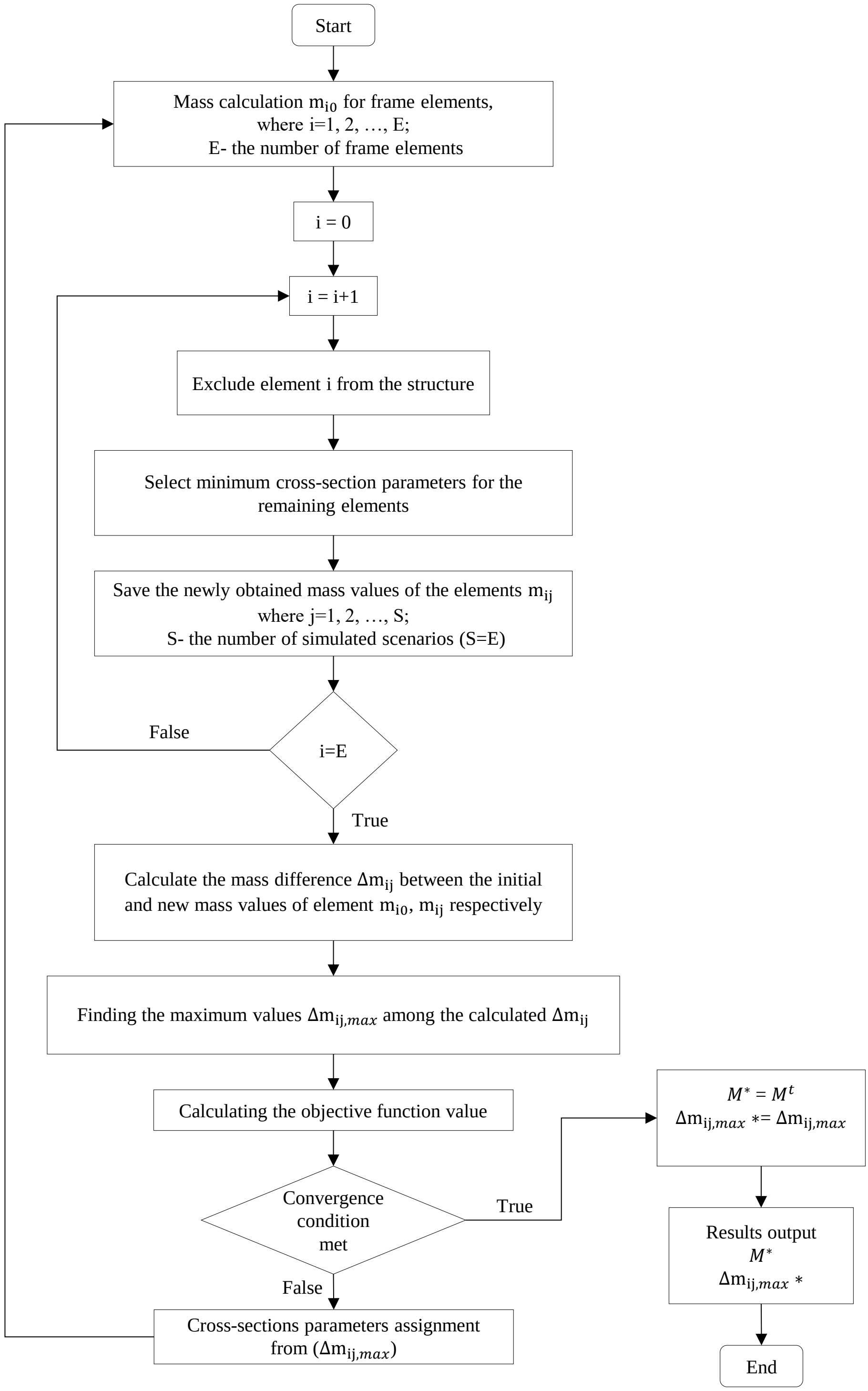

Fig.2. Block diagram of the algorithm for finding the minimum of the objective function.

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.

$$\Delta M = \frac{M_{t-1} - M_t}{M_{t-1}} \leq \varepsilon_M \tag{2}$$

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; $\varepsilon_M -$ 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.

$$\sigma_{\Delta m} \leq \varepsilon_\sigma \tag{3}$$

where $\sigma_{\Delta mi} -$ is standard deviation of mass change for frame elements; $\varepsilon_\sigma -$ 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.

3 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.

4 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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