DOI:10.22337/2587-9618-2025-21-3-22-32

OPTIMAL DESIGN OF TIMBER-FRAME BUILDINGS

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Abstract. The problem of optimal design of timber frame structures is addressed. A computational algorithm has been developed and tested for selecting the cross-sectional areas of structural elements to minimize material volume while satisfying code requirements for strength and stiffness. The mathematical model is formalized as a nonlinear programming problem and solved using a method based on a modified Lagrange function, which ensures a wide convergence region. The algorithm was implemented in the MathCAD software environment, ensuring clarity and making it accessible to design engineers. To verify the optimization results, validation calculations were performed using the Lira-Soft software (CAD system). The research results demonstrated the robust convergence of the developed algorithm and the high accuracy of the obtained solutions. A demonstration of its practical applicability is provided using an example of an actual frame structure.

Keywords: timber frame buildings; optimal design; Lagrangian function; nonlinear programming; finite-element analysis

ОПТИМАЛЬНОЕ ПРОЕКТИРОВАНИЕ ДЕРЕВЯННЫХ КАРКАСНЫХ ЗДАНИЙ

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Аннотация: Рассмотрена проблема оптимального проектирования деревянных каркасных сооружений. Разработан и апробирован вычислительный алгоритм, позволяющего подбирать площади поперечных сечений конструкций из условия минимума объем материала при соблюдении нормативных ограничений по прочности и жесткости. Математическая модель формализована в виде задачи нелинейного программирования, где использован метод на основе модификации функции Лагранжа, имеющий широкую область сходимости. Реализация алгоритма выполнена в среде пакета MathCAD, что обеспечивает его наглядность, делает его доступным и понятным для инженеров-проектировщиков. Для верификации результатов оптимизации проведен их поверочный расчет в ПК LIRA SOFT. Результаты исследования продемонстрировали устойчивую сходимость разработанного алгоритма и высокую точность полученных решений. Дана демонстрация его практической применимости на примере реальной каркасной конструкции.

Ключевые слова: деревянные каркасные здания, оптимальное проектирование, функция Лагранжа, нелинейное программирование, конечно-элементный анализ

INTRODUCTION

In recent years, there has been a significant increase in interest in optimization methods for the design of timber structures. Research is focused on finding optimal shapes, cross-sectional dimensions, and element layout schemes that enable the minimization of material consumption and construction costs while ensuring the required strength and stiffness. For instance, studies [1-3] address the application of genetic algorithms for optimizing beams and trusses. In [4], methods for optimizing the geometry of timber frame structures using nonlinear finite-element analysis are considered. References [5-11] investigate the optimization of connections in timber structures, taking into account their flexibility and influence on overall load-bearing capacity.

Despite the progress achieved, existing optimization methods often face several limitations. Many require significant computational resources and are complex to implement in practice. Conse-

quently, there is a need to develop an efficient, transparent, and accessible tool for the optimal design of timber frame structures. Such a tool should account for the specific behavior of timber and allow design engineers to control each stage of the optimization process. This would enhance the competitiveness of timber construction and broaden its scope of application.

The objective of this research is the development and testing of a computational algorithm for the optimal design of timber frame structures, based on the application of the Lagrange function and its modification, and implemented within the MathCAD mathematical software environment. Unlike existing approaches, this algorithm aims to strike a balance between computational efficiency, transparency, and adaptability to specific design conditions.

The main stages of the research are as follows:

1. Development of a mathematical model for the optimal design of timber frame structures, incorporating code requirements for strength, stiffness, and stability.
2. Implementation of the computational design optimization algorithm within the MathCAD environment.
3. Testing of the developed algorithm using an example of an actual frame structure.
4. Assessment of the reliability of the optimal design through verification analysis using the LIRA-SOFT software.
5. Evaluation of the efficiency and practical applicability of the developed algorithm.

1. MATERIALS AND METHODS

The design calculation for timber frame structures is carried out under the criterion of minimum weight (or volume). In this formulation, the design problem can be posed as an optimization task, where the feasible domain of the structures is constrained by regulatory requirements for strength and stiffness. One of the most versatile and robust methods for optimal design employs a modified Lagrangian function, which serves to enlarge the convergence domain of the underlying algorithm [12]. The problem is thus cast as a nonlinear programming task, in which the design variables – here, the cross sectional areas of the members – are sought within prescribed bounds.

Mathematical Model Used in the Optimization Problem

We present the mathematical model, formulated as a nonlinear programming problem

$$\text{Find} \quad \min f(x), \quad x \in E^{nx}, \tag{1}$$

subject to the following constraints:

$$g_j\left(x, P(x)\right) \le 0, \quad j = 1,2,...m, \tag{2}$$

$$x_i^L \le x_i \le x_i^U, \quad i = 1,2,...nx. \tag{3}$$

Here $f(x)$ – is the objective function (the volume or weight of the structure under consideration);

$\{X\}$ – is the vector of unknown (or design) variables over the interval $\{X^L\}$-$\{X^U\}$ (the cross-sectional parameters of the elements);

nx – is the number of these variables;

$g_j(x)$ – are the constraint functions for strength, stiffness, and stability, $j=1,..., m$;

$P(x)$ – denotes the state parameters of the system (displacements and internal forces developing in the structure), which depend on the design variables x,

$\{P(x)\} = \psi(\{\delta(x)\}, (S(x)\})$, here,

$\{\delta_i(x)\}^T = \{u_i(x)\ v_i(x)\ w_i(x)\ \varphi_{xi}(x)\ \varphi_{yi}(x)\ \varphi_{zi}(x)\}$ – displacement vector at node i of the FE model in 3D space (x,y,z);

$\{S_k(x)\}^T = \{N_k(x)\ \ Q_{yk}(x)\ \ Q_{zk}(x)\ \ M_{xk}(x)\ \ M_{yk}(x)\ M_{zk}(x)\}$ – internal force vector at section k of the spatial FE model.

The equilibrium (state) equation of the system in terms of the nodal displacements is given by:

$$[K(x)]\ \{\delta(x)\} = \{F\},$$

where $[K(x)]$ – is the stiffness matrix of the system; $\{F\}$ – is the vector of external loads.

For a spatial pin-jointed truss system:

$$\{\delta_i(x)\}^T = \{u_i(x)\ v_i(x)\ w_i(x)\},$$
$$\{s_k(x)\}^T = \{N_k(x)\}.$$

The most resource-intensive are the constrained extremum solver module and the finite-element analysis module.

To solve the constrained optimization problem, we will use the Lagrangian function F_L

$$F_L = f(x) + \{Y\}^T[\delta]\{g\}. \qquad (4)$$

Here $\{Y\}$ – is the vector of Lagrange multipliers; $[\delta]$ – is a diagonal matrix of Boolean variables, where δ_{jj} =1, if $j \in M_{ПА}$, and δ_{jj} =0 otherwise, where $M_{ПА}$ – denotes the set of potentially active constraints.

To expand the convergence domain of the search algorithm, we introduce a modification of the Lagrangian function, denoted as *Fp*:

$$FP = k_f F_L + 0{,}5\{g\}^T[\delta][k]\{g\}, \qquad (5)$$

The search algorithm for solving problem (1–3) includes two main operations at each iteration: searching for the parameter set $\{X\}$ by minimizing the modified Lagrangian function *Fp* and updating the dual variables $\{Y\}$, which are determined from the stationarity condition of the Lagrangian function F_L and the modified function *Fp* with respect to *X*:

$$y_j^{t+1} = \max\left(0, y_j^t + \frac{k_{jj}^t}{k_f^t} g^*\left(X^{t+1}\right)\right). \qquad (6)$$

In expression (5), [k] – is the penalty coefficients matrix, and k_f – is the scaling factor for the Lagrange function. Figure 1 shows a flowchart of the sequence of operations within the iterations of the search algorithm, a full description of which is given in [12].

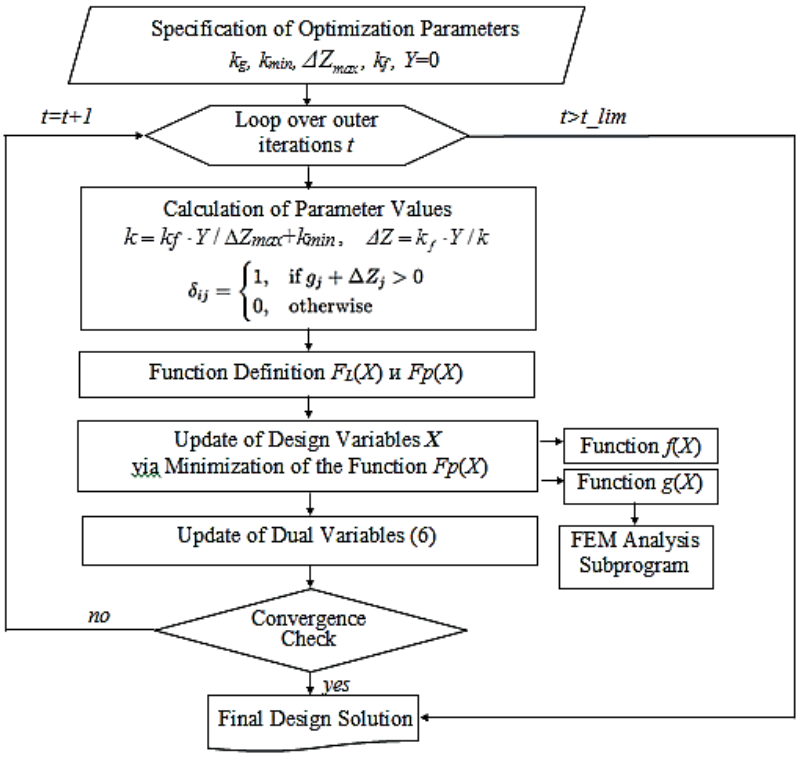


Figure 1. Flowchart of the sequence of computational operations during the iterations

If the structure is statically indeterminate, determining the cross-sectional parameters at each iteration requires recalculating internal forces and displacements by invoking the *FE* analysis subprogram. In this subprogram, the stiffness matrix is assembled using the system's equilibrium matrix [*A*] and flexibility matrix [*B*].

$$[K]=[A][B]^{-1}[A]^{T}$$

Consequently, if node positions are not varied, the equilibrium matrix [*A*] requires no reassembly during the iterative process. The iteration exit criteria at step t are:

$$\left|X^{t+1}-X^{t}\right|\le\varepsilon_{x}\left|X^{t}\right|,\qquad \left|\overline{g}\right|\le\varepsilon_{g}, \tag{7}$$

where $\left|\overline{g}\right|$ – is the set of potentially active constraints; ε_x, ε_g – denote specified convergence tolerances.

Let us consider the specifics of implementing this algorithm in the MathCAD software environment. The minimization of the modified Lagrangian function *Fp*(*X*) is performed using the methods embedded in this package. The automatic termination is controlled by the user according to condition (7).

This approach to the solution offers several advantages: the sequence of operations is clear and logically structured, the algorithm can be reproduced without programming skills, and its implementation only requires knowledge of MathCAD operation principles [13].

Example of frame optimization in the MATHCAD system

To verify the functionality and reliability of the optimization method, a sample problem of optimal design for a 36-bar timber frame structure was solved. The task requires selecting cross-sectional areas for elements of the timber frame structure shown in Figure 2, where the structure is displayed with coordinate axes

Input data: *d*=3 m, *h*=3 m. The material is Grade 1 pine, with an elastic modulus along the grain *E* = 10000 MPa, allowable compressive strength R_c =13,365 MPa, and allowable tensile strength R_t =8 MPa.

Two loading cases are specified (see Figure 3):

- first case: force *P* = 25 kN applied in the directions of the *x, y, z* axes at node 1;
- second case: force: *P* = 25 kN applied in the negative *z*-direction at nodes 1, 2, 3, and 4.

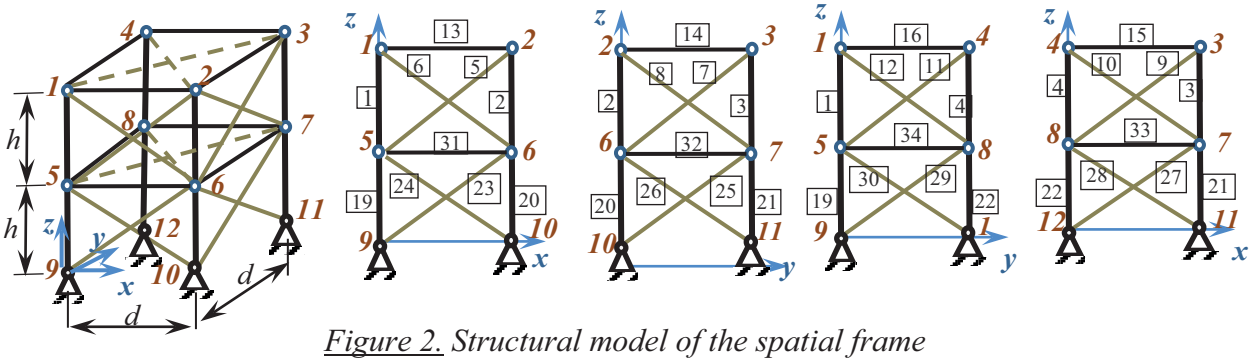


Figure 2. Structural model of the spatial frame

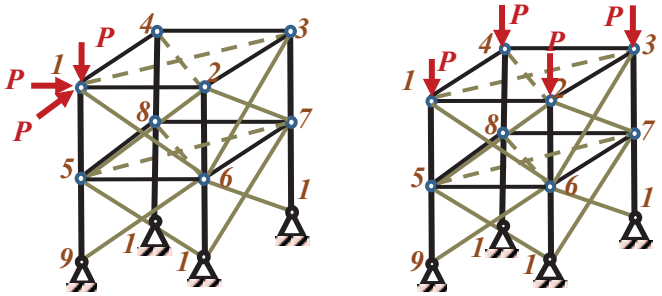


Figure 3. First and second loading cases

The structural elements are grouped by cross-sectional types, as shown in Table 1. On each floor, four types of elements are considered: 4 columns, 8 braces, 4 beams, and 2 horizontal ties.

Table 1. Distribution of cross-sectional areas (A_i) of elements by groups

Variation parameters							
x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8
A_1:A_4	A_5:A_{12}	A_{13}:A_{16}	A_{17}:A_{18}	A_{19}:A_{22}	A_{23}:A_{30}	A_{31}:A_{34}	A_{35}:A_{36}

The cross-sectional areas in each group were varied within the range of 6 to 90 cm^2.
The objective is *to minimize* the structure's volume

$$f = \sum_{k=1}^{nel} A_k l_k$$

where *nel* = 36; A_k , l_k – are the cross-sectional area and length of the *k*-th element.
The following constraint functions are adopted.
The strength check for the *i*-th group of structural cross-section types (8 constraints) is carried out according to the formulas of *«СП 64.13330.2017 Деревянные конструкции»*.

For compressed elements

$$g_i = \frac{|N_i|}{\varphi \cdot x_i \cdot R_c} - 1 \le 0,$$

For tensioned elements

$$g_i = \frac{N_i}{x_i \cdot R_t} - 1 \le 0.$$

Here, x_i – is the design variable, N_i – is the design axial force for the most heavily loaded member in the *i*-th group (taken as the maximum force from the two loading cases). φ - is the buckling reduction factor, calculated per Formulas (13–16) of «*СП 64.13330.2017*».
For structural members satisfying $\lambda < 70$

$$\varphi = 1 - 0{,}8\left(\frac{\lambda}{100}\right)^2.$$

For structural members satisfying $\lambda > 70$

$$\varphi = \frac{3000}{\lambda^2}, \quad \text{where}$$

$$\lambda = \frac{l}{r}, \quad r = \sqrt{\frac{A_s}{12}}.$$

The stiffness check is based on the maximum displacement, which occurs at node 1. Therefore, one constraint from the first loading case along the *x-axis* is considered.

$$g_9 = \frac{\delta_1}{[\Delta]} - 1 \le 0. \qquad [\Delta]=1{,}4 \text{ cm}.$$

Solution. Computational operations during iterations of the search algorithm are illustrated in Figure 1. The minimization problem for function *Fp* was solved using built-in MathCAD methods:

- Levenberg-Marquardt method;
- Conjugate gradient method;
- Quasi-Newton method.

The program automatically switches between these methods until convergence is achieved by one of them.

2. RESULTS AND DISCUSSION

Optimization results (Figure 4) provide the cross-sectional areas for each member group in the frame structure.

Figure 4. Optimization results

Optimal parameters (cm²)	
1	74,46636995
2	88,78768792
3	42,26213826
4	78,17657518
5	82,57623377
6	78,06506049
7	6
8	6

Stress constraint thresholds	
1	-3,89058E-08
2	1,78E-07
3	2,14E-07
4	-1,03054E-06
5	-1,06004E-06
6	3,09E-07
7	-0,51288
8	-0,51288

Displacement constraint at Node 1
-0,76425

Analysis of constraint functions reveals that strength constraints for the first five member groups are active (critical).

Convergence plots for both the objective function and constraint functions across iterations are presented in Figure 5. The iterative cycle terminated based on condition (7). The constraint residuals demonstrated high precision (10^{-7}). The optimization yielded a final objective function value of 8.84109×10 cm^3.

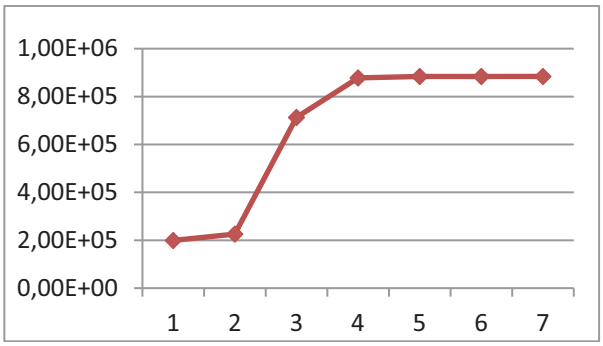


Figure 5. Objective function evolution during iterations

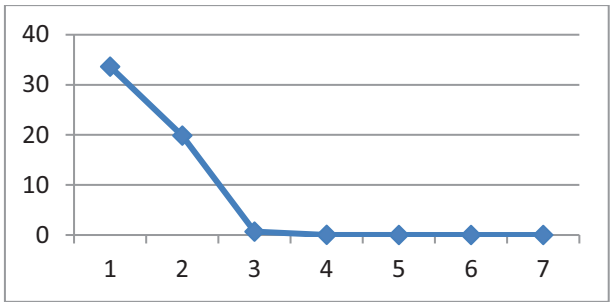


Figure 6. Evolution of maximum constraint residuals during iterations

To verify the calculation results, we will compute *the complete* vector of strength and stiffness constraints in the MathCAD program, where the obtained solution is checked. The cross-sectional area parameters here are taken from the optimization program..

Analysis of the obtained values shows that the strength constraints are active for second-floor columns under loading case 2. For all other element groups, the constraints are active under loading case 2. For first-floor beams and bracing elements, the constraints are satisfied with a safety margin.

Table 2. Strength Verification

		Elements	Loading Case 1	Loading Case 2
Floor 2	**Columns**	**1**	-0,791	**-3,90E-08**
		2	-0,966	**-3,90E-08**
		3	-0,415	**-3,90E-08**
		4	-0,966	**-3,90E-08**
	Braces	**5**	-0,907	-0,787
		6	**1,78E-07**	-0,787
		7	-0,88	-0,787
		8	-0,617	-0,787
		9	-0,617	-0,787
		10	-0,88	-0,787
		11	-0,907	-0,787
		12	**1,78E-07**	-0,787
	Beams	**13**	**2,15E-07**	-0,972
		14	-0,941	-0,972
		15	-0,941	-0,972
		16	**2,15E-07**	-0,972
	Bracings	**17**	**-1,03E-06**	-0,972
		18	-0,956	-0,972
Floor1	**Columns**	**19**	-0,77	-0,153
		20	-0,752	-0,153

		21	**-1,06E-06**	-0,153
		22	-0,752	-0,153
	Braces	**23**	-0,791	-0,777
		24	-0,365	-0,777
		25	-0,939	-0,777
		26	**3,09E-07**	-0,777
		27	**3,09E-07**	-0,777
		28	-0,939	-0,777
		29	-0,791	-0,777
		30	-0,365	-0,777
	Beams	**31**	-0,946	-0,513
		32	-0,763	-5,13E-01
		33	-0,763	-5,13E-01
		34	-0,946	-0,513
	Main	**35**	-0,956	-0,513
		36	-0,753	-0,513

The stiffness constraints are satisfied with significant safety margins for both loading cases.

Verification Analysis of Spatial Frame in LIRA-SOFT Software

Using the selected cross-sections, a verification analysis was performed in LIRA-SOFT software (Figs. 7, 8). The internal forces obtained in LIRA-SOFT and MathCAD calculations showed complete agreement. The results confirm the correctness of the finite element analysis implementation within the optimization algorithm.

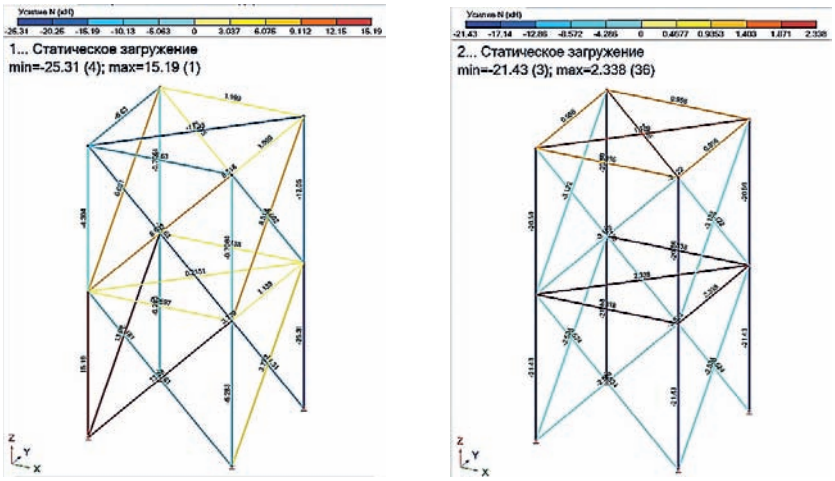


Figure 7. Internal forces from Loading Cases 1 and 2 in LIRA-SOFT

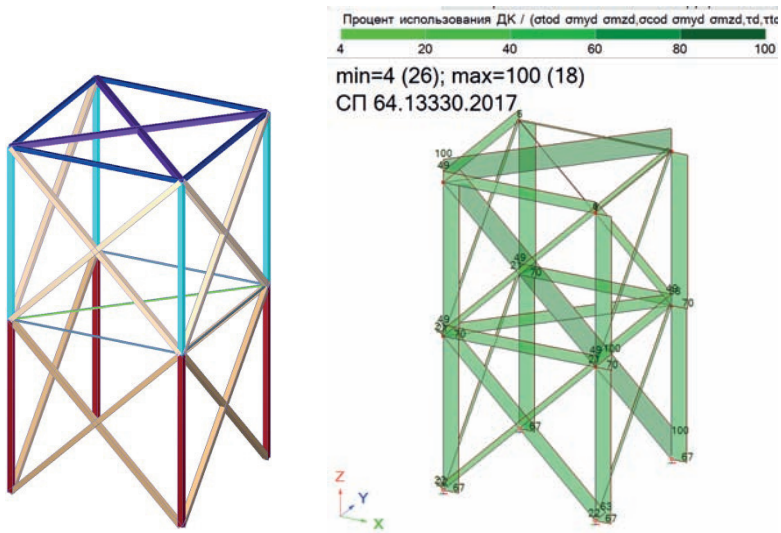


Figure 8. Original Frame Model and Section Utilization Percentage in LIRA-SOFT

An optimal design of a spatial timber frame has been obtained, with the optimization algorithm demonstrating stable convergence and high accuracy of results.

Factors affecting algorithm performance: structure size (number of members, nodes); degree of static indeterminacy; computer processing power; efficiency of finite element analysis implementation in MathCAD; choice of optimization method.

Advantages:

- Clear and logically transparent algorithm
- Implementation possible without specialized programming skills (basic MathCAD knowledge sufficient)
- Easy modification and adaptation to specific problems

Limitations:

- No automatic iteration exit (requires user monitoring) - inconvenient for large/complex problems
- Potentially lower performance compared to specialized optimization software
- Limited MathCAD functionality
- Implementation simplicity: relatively easy for MathCAD users, but lack of automation may hinder non-specialists
- Scalability: performs poorly for very large structures due to FEA computational complexity and lack of automated optimization

The timber material's influence on optimization algorithm development should be noted. The algorithm accounted for these parameters: design compressive strength, design tensile strength, and elastic modulus. Strength, stiffness, and stability verifications were completed.

However, comprehensive efficiency evaluation requires testing on more examples with variations in structure size, geometry, and loading conditions. Also necessary is comparing algorithm runtime against other known frame structure optimization algorithms.

CONCLUSION

An optimization algorithm for designing frame structures has been developed and implemented in the MathCAD environment. The algorithm combines the finite element method for analyzing structural stress-strain states with a modified Lagrange function minimization method to determine optimal cross-sectional areas while satisfying strength, stiffness, and stability constraints.

The key advantage of this approach is its transparency and accessibility, enabling engineers with basic MathCAD knowledge to understand and control the optimization process, unlike complex commercial packages that function as "black boxes." Experimental results for a 36-bar structure demonstrated the algorithm's functionality.

However, it should be noted that the algorithm's performance is constrained by MathCAD's capabilities. The complexity of finite element analysis makes it unsuitable for optimizing large and complex structures within reasonable timeframes. Moreover, the need for manual convergence monitoring requires user expertise and may significantly increase design time.

Despite these limitations, the developed algorithm can be valuable for teaching structural optimization fundamentals to students and engineers, as well as for solving small-scale problems where transparency and manual adjustment capabilities are essential.

Future research should focus on improving this optimization algorithm, for example by automating the convergence process. Additionally, more extensive experimental studies are necessary to evaluate the algorithm's effectiveness across various timber structure types and compare it with existing approaches.

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