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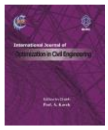

OPTIMIZATION OF SPACE STRUCTURES IN INELASTIC REGION USING FORCE ANALOGY METHOD BASED ON SHUFFLED SHEPHERD OPTIMIZATION ALGORITHM (SSOA)

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ABSTRACT

The optimization process of space structures considering the nonlinear material behavior requires significant computational efforts due to the large number of design variables and the complexities of nonlinear structural analysis. Accordingly, the Force Analogy Method (FAM) serves as an efficient tool to reduce computational workload and enhance optimization speed. In this study, the weight optimization of space structures in the inelastic region under seismic loading is carried out using the Shuffled Shepherd Optimization Algorithm (SSOA), with the nonlinear structural analysis based on the FAM. To do this, the FAM formulation for axially loaded members of space structures under seismic forces is presented. Subsequently, weight optimization is performed on two double-layer space structures: a flat double-layer structure with 200 members and a barrel vault structure with 729 members under the Kobe earthquake record. Based on the results, the optimized design using the inelastic behavior showed that the FAM provided accurate results when compared to the precise nonlinear structural analysis. The optimized design based on the FAM is considered acceptable, and the computational time for the optimization process has been significantly reduced.

Keywords: force analogy method (FAM), nonlinear analysis, shuffled shepherd optimization algorithm (SSOA), space structure.

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1. INTRODUCTION

Throughout their service life, many structures may undergo inelastic deformations when subjected to various loads, including seismic forces. Space structures, due to their specific applications in industries, are no exception. These structures feature members that experience axial deformations, which can also result in inelastic deformations under external forces such as seismic loads. The onset of inelastic deformations depends on the magnitude of these external forces and the structural parameters of the space structure. Thus, space structures under seismic forces are expected to exhibit nonlinear behavior, with inelastic deformations in their members. Therefore, it is essential to utilize an optimal and effective method for nonlinear analysis of space structures when simulating the behavior of axially loaded members under both static and dynamic loads. However, the traditional approaches in nonlinear Finite Element (FE) analysis for optimal design, especially for space structures, are time-consuming and computationally expensive. Therefore, it is crucial to develop a simple yet accurate dynamic analysis technique for optimal design and to establish a method that models nonlinear behavior at an optimal cost within a reasonable time frame. The Force Analogy Method (FAM) is an effective strategy for analyzing various structures with nonlinear behavior, including space structures. This method is based on the residual (inelastic) displacement, where the nonlinear material behavior is represented by changes in the displacement vector instead of changes in the stiffness matrix of the structure. The FAM formulates an inelastic deformation as a single Degree of Freedom (DOF), and the stiffness matrix of the structure is calculated once during the nonlinear analysis process [1]. Thus, the FAM is expected to accelerate the optimization process for space structures with numerous members. Since the most time-consuming step in the optimization process is the structural analysis, particularly the nonlinear analysis, the FAM can significantly enhance the efficiency of the optimization process for structures with nonlinear behavior.

In recent years, extensive research has been conducted to apply optimization algorithms to solve various engineering problems. Most of the earlier studies on structural optimization assumed linear material behavior, with nonlinear behavior being addressed only in a few cases [2-4]. Other studies have developed techniques for nonlinear structural analysis, focusing primarily on improving computational speed and accuracy. Wong and Yang (1999) were among the first researchers to apply the FAM to structural engineering. In their study, the FAM was formulated in force-deformation space, and a nonlinear dynamic analysis was performed. The FAM was applied using inelastic deformations modeled as a 1-DOF system, with the stiffness matrix being calculated and applied only once during the nonlinear dynamic analysis [5]. Wong and Wang (2007) proposed an FAM-based analytical technique for inelastic dynamic analysis. Their study investigated the displacements at plastic hinges at the ends of members and the rigid panel zones of moment-resisting frames. The technique determined the required stiffness matrix for members with rigid ends using the displacement method, followed by static condensation to modify the stiffness matrix. Numerical simulations were conducted for seismic analysis of a single-degree-of-freedom system. The results indicated that the end displacements of plastic hinges significantly affected the seismic response of the structure and must be considered in dynamic analysis [6]. Song and Li (2012) conducted an analysis of steel structures using the FAM. They proposed a novel FAM-based approach to study the inelastic behavior of steel structures under dynamic loads.

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The model assumed nonlinear behavior for the steel frame and plastic hinges at both ends of the beam. The results, including graphs of maximum interstorydisplacement and the flexural resistance moments in the plastic hinges, demonstrated that the proposed method was faster and more accurate than conventional methods in simulating the nonlinear behavior of structures [7]. Li et al. (2013) used a physical theory-based model within the FAM. The model provided an accurate, efficient, and stable method for dynamic analysis in the state-space. The results showed that the model was relatively simple and efficient, providing acceptable results [8]. In 2013, Li et al. proposed a formulation for analyzing seismic damage in reinforced concrete (RC) frames using the FAM, considering stiffness deterioration. The model assumed the ends of beams and columns to be damaged hinges to represent cracking damage. The results demonstrated the effectiveness of the model in predicting the damage levels in RC moment-resisting frames [9]. Li et al. (2015) introduced an FAM-based formulation for the nonlinear analysis of concrete bridges. They examined the seismic performance of the bridges based on the fundamental concepts of the FAM. Two local biaxial plastic mechanisms (rotational and sliding hinges) were proposed to simulate the nonlinear flexure-shear interaction in the bridge piers. The formulation was compared with experimental results, and the biaxial plastic mechanisms provided satisfactory accuracy [10]. Safaei et al. (2019) compared the performance and efficiency of the FAM in nonlinear static (pushover) analysis with other common finite element methods in SAP. They also investigated the effects of elastic axial deformations on the structural performance by modifying the stiffness matrices of the members. The study evaluated six 2D steel frames using various methods, with the FAM proving efficient in seismic performance analysis [11]. Bahar and Bahar (2018) used the FAM to examine various static condensation methods in nonlinear structural analysis. In their study, they incorporated Rayleigh damping into the static condensation formulation. The results indicated that the FAM provided comparable performance to other finite element methods [12]. Kaveh and Zaerreza (2022) investigated the optimal design of framed structures. They used the force method to reduce the time required for optimization. Their study compared the performance and speed of the force method against the displacement method in the optimal design of frame structures using an improved PSO algorithm. The results showed that both analytical methods had similar accuracy, but the force method was faster and required less computational time [13]. In 2023, Kaveh and Rezazadeh Ardabili examined the optimization of multi-story concrete structures using an Improved Plasma Generation Optimization (IPGO) algorithm. Their study evaluated the effectiveness of the proposed algorithm in the optimal design of three-dimensional concrete frames under lateral seismic forces, in compliance with ASCE 7 requirements. The results showed the proposed algorithm's efficiency in optimizing concrete frames under seismic loading [14]. Kaveh and Shabani Rad (2023) used the force method for linear structural analysis in optimizing the weight of truss structures. Their study introduced an Improved Vibration Particle System (IVPS) algorithm as a new method for truss optimization. The results indicated that the proposed algorithm outperformed other available algorithms, and the use of the force method increased the optimization speed [15].

As can be seen, numerous studies have focused on improving the modeling of inelastic behavior in structures. However, considering the nonlinear behavior in the optimization design of structures involves substantial computational costs. This challenge has led to the limited investigation of inelastic behavior in space structures, due to the large number of

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design variables and the complexity of nonlinear analysis. Therefore, the use of methods such as the Force Analogy Method (FAM) can provide an efficient tool for optimizing space structures while considering nonlinear material behavior. In this study, the weight optimization of space structures is considered, accounting for the nonlinear material behavior using the approximate FAM. Instead of calculating the stiffness in the inelastic region, the FAM considers displacement, followed by the calculation of force in the inelastic region, to perform nonlinear analysis. Consequently, the stiffness matrix is calculated only once in the nonlinear analysis for optimization, with the analysis of the structure considering the forces in the inelastic region. This study details the FAM formulation for the axial members of space structures and the impact of seismic forces on the structure. Finally, the validity of the method is tested by comparing the results of a 2D truss analysis based on the FAM with precise nonlinear analysis. The optimization process using the Shuffled Shepherd Optimization Algorithm (SSOA) for two space structures under seismic loading in the inelastic region is also performed. The optimization results indicate the effective performance of the proposed approach.

2. FORCE ANALOGY METHOD FOR SPACE STRUCTURE

2.1 FAM for Axial Loaded Members

As previously mentioned, the Force Analogy Method (FAM) is based on the behavior of a structure in the elastic range and nonlinear displacements. Fig. 1 depicts this for a member under axial tensile load [10].

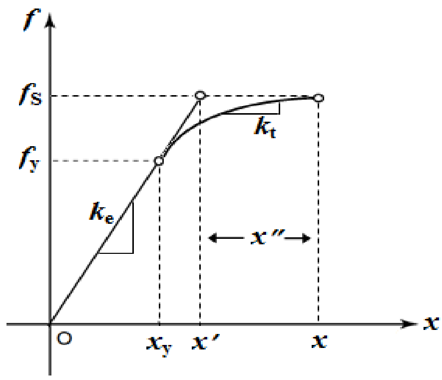

Figure 1: Force-Displacement diagram in the tensile region

Accordingly, in an axially loaded member, the force corresponding to the total displacement x is expressed based on the stiffness of the member in the elastic range.

$$f_s = k_e x' \tag{1}$$

Where f_s represents the force corresponding to the total displacement, considering the nonlinear behavior of the structure, k_e is the stiffness of the member in the elastic range, and x' is the elastic displacement. The inelastic or residual displacement (x'') can be calculated as the difference between the total displacement and the elastic displacement.

$$x'' = x - x' \tag{2}$$

Using Eqs. (1) and (2), Eq. (3) can be derived.

$$f_s = k_e\left(x - x''\right) \tag{3}$$

which shows the displacement of the member based on the force. Since the elastic displacement is not constant and changes with the applied force, f_s, the FAM does not alter the stiffness but, by varying the displacement, it obtains the force corresponding to the structure's nonlinear behavior [16].

On the other hand, for space structures with axial members, the FAM requires that the initial stiffness be the same in both tension and compression. This paper utilizes a physical theory-based model as the base for developing a modified version of the FAM [17]. Thus, Eq. (3) can also be considered valid for compressive axial loads, based on the equality of stiffness in tension and compression. However, it's important to note that, under compressive loading, there is a possibility of buckling before yielding for certain members of the space structure. Therefore, in the FAM for the compressive state, the buckling behavior of members must also be considered. In this context, Fig. 2 shows the behavior model of an axially loaded member under compressive forces, with a potential for buckling [8].

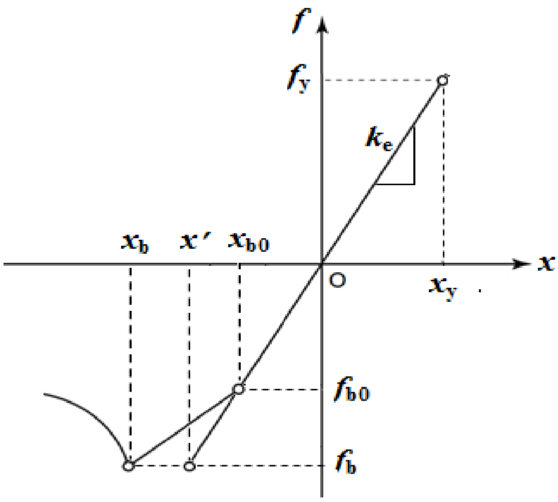

Figure 2: Force-Displacement diagram in the compressive region for buckling

As shown in Fig. 2, the member's behavior under compression is assumed to have the same stiffness as in the tensile region until buckling occurs. Here, f_b represents the buckling force, and x_b the corresponding displacement, which is regarded as the total displacement, x.

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If the elastic line is extended to the buckling force, f_b, the corresponding elastic displacement x_b will be obtained, which is known as the total displacement x. Using a similar process as for tensile loading, the inelastic compressive displacement due to buckling can be expressed as:

$$x'' = x_b - x' \tag{4}$$

where x'' denotes the plastic displacement of the member, as with compressive and tensile loads. Likewise, the force-displacement correlation in the presence of possible buckling can be written as:

$$f_b = k_e (x - x'') \tag{5}$$

Thus, the force-displacement equation under buckling is similar to the force-displacement equations under tension and compression. In the FAM, $x'' = 0$ as long as the axially loaded member is elastic, while it is obtained based on the force when the member undergoes a plastic deformation or buckling. The general plastic displacement can be written as [16]:

$$x'' = (1-\alpha)(x - x_y) \tag{6}$$

where α is the axial stiffness-hardening factor, while x_y is the displacement corresponding to the yielding force f_y. It should be noted that the compressive yielding stress and tensile yielding stress were assumed to be the same. In general, for axially loaded members under compression or tension in the FAM, the force and displacement can be correlated based on Eqs. (3), (5), and (6).

$$f = \alpha k_e (x - x_y) + f_y \tag{7}$$

2.2 State-Space Nonlinear Dynamic Response for the FAM

As explained in the previous section, the core concept of the FAM is that displacement changes, rather than stiffness changes, define the force. Therefore, the total displacement of the structure can be considered as the sum of the elastic and plastic displacements. As such, Eqs. (2) and (4) can be expressed in vector form for a multi-degree-of-freedom system, such as space structures [5].

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$$X'(t)=\begin{Bmatrix} x_1'(t) \\ x_2'(t) \\ \vdots \\ x_n'(t) \end{Bmatrix}=X(t)-X''(t)=\begin{Bmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_n(t) \end{Bmatrix}-\begin{Bmatrix} x_1''(t) \\ x_2''(t) \\ \vdots \\ x_n''(t) \end{Bmatrix} \tag{8}$$

where n denotes the number of DOFs. The insertion of Eq. (8) into the dynamic equilibrium equation gives [7].

$$M\ddot{X}(t)+C\dot{X}(t)+KX(t)=-M\ddot{g}(t)+KX''(t) \tag{9}$$

where $\boldsymbol{M}$ is the mass matrix, $\boldsymbol{C}$ is the damping matrix, $\boldsymbol{K}$ is the stiffness matrix, and $\ddot{g}(t)$ reflects the earth's motion. To express Eq. (9) in a state-space form, the state vector is defined as:

$$Z(t)=\begin{Bmatrix} X(t) \\ \dot{X}(t) \end{Bmatrix} \tag{10}$$

The differential equation governing the state space can be written as [16]:

$$\dot{Z}(t)=AZ(t)+H+GX''(t) \tag{11}$$

where $\boldsymbol{A}$ is the state transition matrix, $\boldsymbol{H}$ is earth's motion matrix, and $\boldsymbol{G}$ denotes the plastic deformation transition matrix, which is defined as:

$$A=\begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix},\quad H=\begin{bmatrix} 0 \\ -\ddot{g}(t) \end{bmatrix}\quad and \quad G=\begin{bmatrix} 0 \\ M^{-1}K \end{bmatrix} \tag{12}$$

Here, $Z(t)$ is obtained by solving Eq. (11).

$$Z(t)=e^{A(t-t_0)}Z(t_0)+e^{At}\int_{t_0}^{t}e^{-Aq}\left[Ha(q)+GX''(q)\right]dq \tag{13}$$

where $a(q)$ is the delta force function to define the ground acceleration based on the time variable q between time steps t_i and t_{i+1}. The value of $Z(t)$ in given time steps is found by solving the integral part in Eq. (13). As a result, the displacement in the given time interval and, thus, the absolute acceleration vector are obtained [16].

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2.3 Formulation of the Optimization Problem

The primary goal of optimization problems in structural design is to minimize weight while adhering to constraints. For skeletal structures like space frames, part of the weight is calculated based on the cross-sectional area of the structural members. Therefore, the cross-sectional area of members can be treated as the design variable in the weight optimization process. In optimization, constraints are crucial and vary depending on the type of structure and optimization problem. For skeletal structures, constraints such as stress limits in the members are typically considered. In this paper, the weight optimization of space structures under seismic loads using FAM-based nonlinear analysis is considered, with the cross-sectional areas as design variables and the member stresses as constraints. The optimization problem is formulated as follows [18].

$$\begin{aligned} &Minimize \quad W = \sum_{i=1}^{ne} \rho_i s_i L_i \\ &Subject\ to \quad \sigma_i \le \sigma_{all} \quad i = 1, 2, \ldots, ne \end{aligned} \tag{14}$$

Where W is the weight of the structure to be minimized, ne is the number of members, and ρ_i , L_i , s_i and σ_i denote the density, length, cross-sectional area, and stress of member i, respectively, and σ_{all} is the allowable stress. To evaluate design (structure) j in the search space, the constraint violation of design j is obtained as [19].

$$c_j = \sum_{i=1}^{ne} \max\left[\left(\left(\frac{\sigma_i}{\sigma_{all}}\right) - 1\right), 0\right] \tag{15}$$

where C_j is the constraint violation of structure j. Once the constraint violations of designs have been measured, the fitness function of design j is calculated as.

$$\phi_j = W_j \left(1 + C_j\right) \tag{16}$$

where ϕ_j is the fitness function of design j across the search space. A design with a larger constraint violation score has a larger ϕ-value and lower fitness. Finally, the optimization problem is formulated for the optimal weight design of space structures [20]. This study used the SSOA to optimize the space structures.

2.4 Shuffled Shepherd Optimization Algorithm (SSOA)

SSOA is a meta-heuristic optimization algorithm introduced by Kaveh and Zaerreza (2020), inspired by the herding behavior of shepherds in the nature [21-22]. In this algorithm, solutions are represented as sheep, and the movement of each sheep guided by the shepherd and the horse searches the design space. The population of sheep is randomly initialized, and their fitness is evaluated based on the objective function. The sheep are then

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ordered according to their fitness and shuffled into *nh* communities. The first *nh* sheepare randomly distributed into communities. Once the first sheeph as been assigned to the first community, *nh* sheep of the remaining population are chosen, reassigning the sheep to communities. This process continues until all sheep are assigned to *nh* communities. Upon completion of shuffling, all communities have the same number of sheep, with the best and worst within each community being the first and last members, respectively. The movement vectors for each sheep are calculated. Naturally, a shepherded attempts to direct sheep towards the horse. Therefore, the design corresponding to the top sheep chosen to move is known as Shepherd ($R_{i,j}$). In each community, two designs (sheep) with higher and lower fitness than the shepherd are randomly chosen. The designs that are better and worse than the sphered are denoted as the horse ($R_{i,h}$) and the shepherd ($R_{i,s}$). To continue directing the sheep toward the horse, the shepherd moves toward the sheep and then toward the horse. Therefore, the movement step of the chosen sheep/shepherd follows Eq. (17) as follows.

$$\begin{aligned} &Stepsize_{i,j} = \alpha \times rand_2 \circ \left(R_{i,s} - R_{i,j}\right) + \beta \times rand_1 \circ \left(R_{i,h} - R_{i,j}\right) \\ &i = 1,2,...,nh \quad j = 1,2,...,ns / nh \end{aligned} \tag{17}$$

where *nh* and ns are the number of communities and the number of sheep, respectively, while $rand_1$ and $rand_2$ are two vectors whose entries are either 0 or 1. These entries are randomly generated between 0 and 1. The control parameters α and β are calculated as:

$$\alpha = \alpha_0 - \frac{\alpha_0}{\max iteration} \times iteration \tag{18}$$

$$\beta = \beta_{\min} + \frac{\beta_{\max} - \beta_{\min}}{\max iteration} \times iteration \tag{19}$$

where *iteration* and max*iteration* denote the current iteration and the maximum number of iterations, respectively. Furthermore, α_0, $\beta_{\max}$ and $\beta_{\min}$ are set by the user. Evidently, a rise in the number of iterations linearly reduces α to zero, while β linearly rises as the number of iterations increases from $\beta_{\min}$ to $\beta_{\max}$. Once the movement step has been calculated for all the sheep in all communities, the new position of each sheep is updated as Eq. (20)

$$R_{i,j}^{new} = R_{i,j}^{old} + Stepsize_{i,j} \quad i = 1,2,...,nh \quad j = 1,2,...,ns / nh \tag{20}$$

Then, $R_{i,j}^{old}$ is replaced with $R_{i,j}^{new}$, and sheep with higher fitness replace the previous sheep. This process is performed for all sheep of all communities. Then, new communities are combined, the sheep are rearranged based on their fitness in descending order, and one iteration is completed. A new iteration begins with re-shuffling sheep. The iterations continue until the discontinuance criterion (the maximum number of iterations) has been met, and the best sheep is introduced as the optimal design.

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3. NUMERICAL EXAMPLES

3.1 Example 1: 2D Truss

In the first example, FAM was used to analyze a 2D truss structure with 12 nodes and 25 members and the results obtained from FAM were compared with the exact method using Opensees, as shown in Fig. 3.

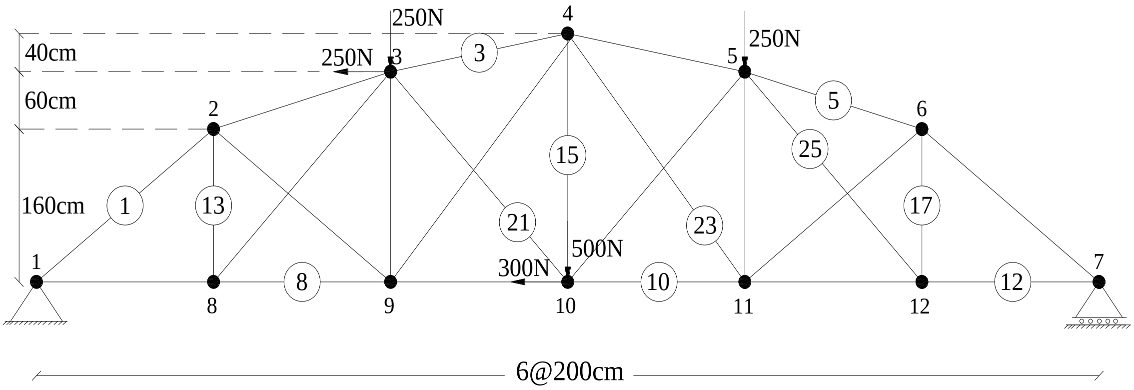

Figure 3: Schematic of the 2D truss

The modulus of elasticity and the density of the materials were 2.01×10^6 *kg/cm*² and 7850 *kg/m*³, respectively. The cross-sectional area of members 1 to 12 was 45.9 *cm*², of members 13 to 17 was 28.5 *cm*², and the remaining members had a cross-sectional area of 39.1 *cm*². The structure was subjected to a nonlinear analysis under the Kobe earthquake records, as shown in Fig. 4.

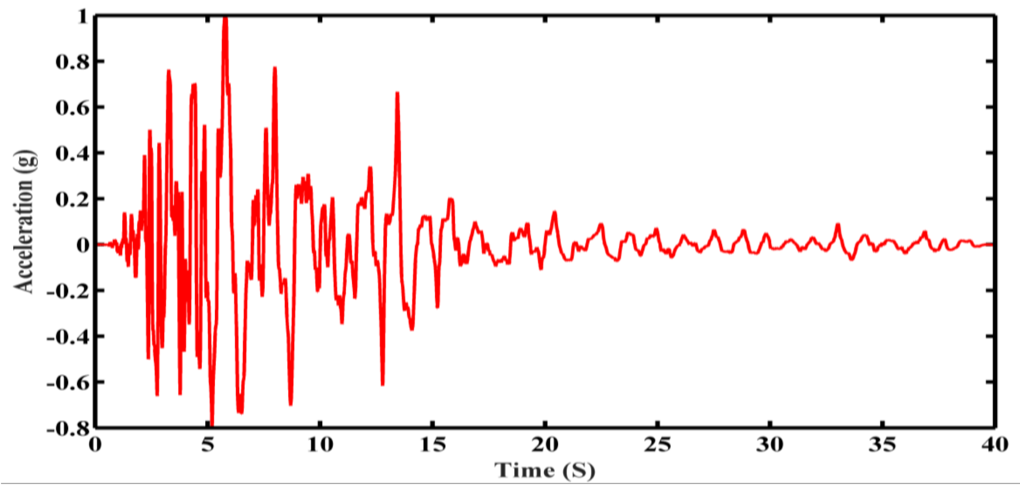

Figure 4: Acceleration records of the Kobe earthquake

For validation of the FAM results, the displacement of node 10 was analyzed. As seen in Fig. 5, the displacement estimated using the FAM is in good agreement with the exact method. Therefore, it can be concluded that the FAM is an accurate method for nonlinear

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analysis. It should be noted that the small discrepancy in the displacement of node 10, shown in Fig. 5, is due to the simplifications made in the Ref. [17] model used in the FAM method.

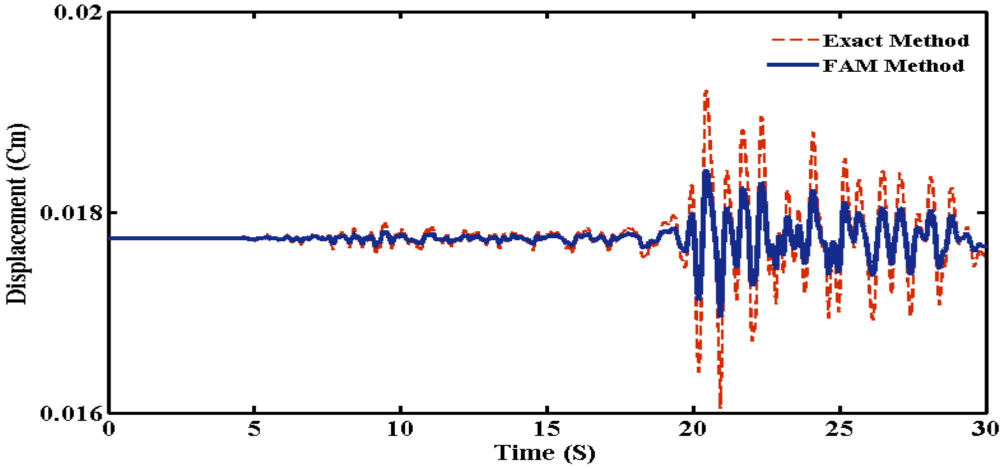

Figure 5: Displacement of node 10 under Kobe earthquake

3.2 Example 2: Double-Layer Barrel Vault with 792 Members

Fig. 6 shows a double-layer barrel vault with 219 nodes and 792 members investigated based on the FAM with nonlinearity and optimization incorporated. The modulus of elasticity and the density of each element were 2.01×10^6 kg/cm^2 and 7850 kg/m^3, respectively. The length, width, and height of the structure were 35 *m*, 30 *m*, and 3 *m*, respectively.

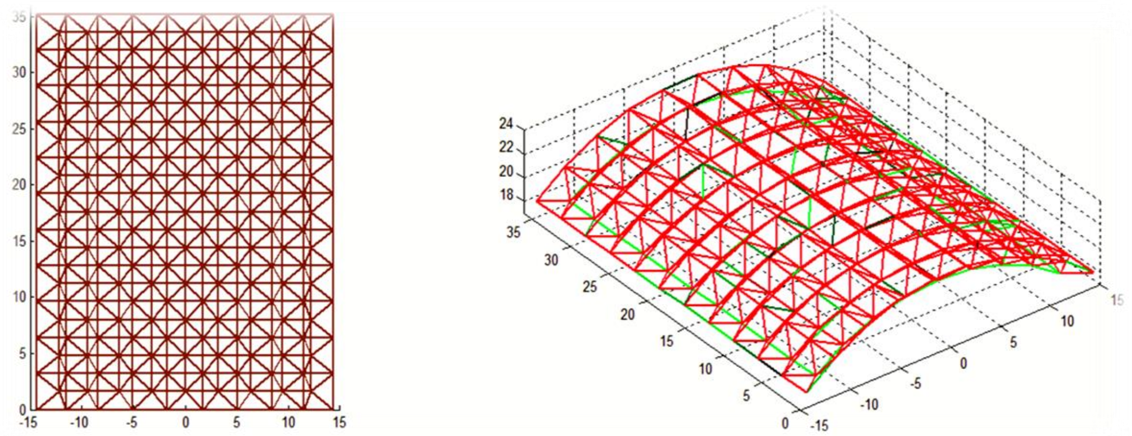

Figure 6: 3D Schematic and plan of the double-layer barrel vault

The structure was subjected to the Kobe earthquake records, as shown in Fig. 4. The members of the barrel vault were divided into 12 groups. As shown in Fig. 7, the members of the upper, lower, and middle layers were classified into four groups.

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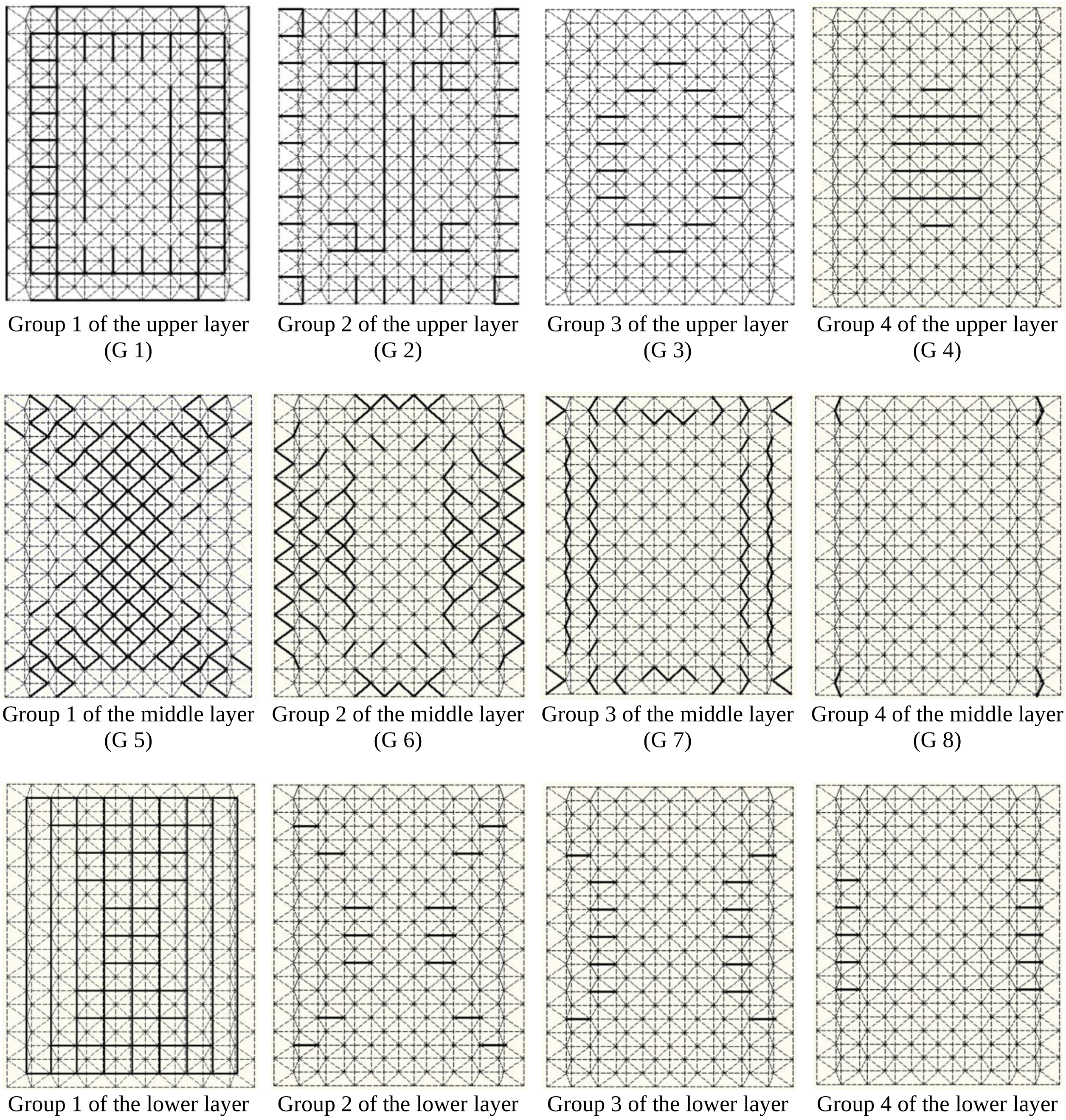

Group 1 of the upper layer (G 1) | Group 2 of the upper layer (G 2) | Group 3 of the upper layer (G 3) | Group 4 of the upper layer (G 4)

Group 1 of the middle layer (G 5) | Group 2 of the middle layer (G 6) | Group 3 of the middle layer (G 7) | Group 4 of the middle layer (G 8)

Group 1 of the lower layer (G 9) | Group 2 of the lower layer (G 10) | Group 3 of the lower layer (G 11) | Group 4 of the lower layer (G 12)

Figure 7: Grouping of barrel vault members

Table 1 provides a list of the cross-sectional types available for the optimization process of the structure's weight, which includes 16 hollow tubular sections. In this table, *D* represents the outer diameter of the tube in millimeters, and *t* is the wall thickness of the tube in millimeters.

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Table 1: List of tubular sections

No	*D* (mm)	*t* (mm)	No	*D* (mm)	*t* (mm)	No	*D* (mm)	*t* (mm)	No	*D* (mm)	*t* (mm)
1	48.3	2.6	5	101.8	3.6	9	139.7	4	13	219.1	4.5
2	60.3	2.9	6	108	3.6	10	159	4.5	14	244.5	6.3
3	76.1	2.9	7	114.3	3.6	11	168.3	4.5	15	273	5
4	88.9	3.2	8	133	4	12	193.7	4.5	16	329.9	5

The optimization of the structure's weight was performed using the SSOA algorithm, with the nonlinear analysis based on the FAM. In order to compare the performance of the FAM, the optimization process was also carried out using the exact nonlinear analysis method in Opensees. That is, the optimization process for the 792-member barrel vault was carried out twice: once using the FAM and once using the Opensees's exact method. The results of both methods, in terms of convergence during the optimization process, are compared in Fig. 8.

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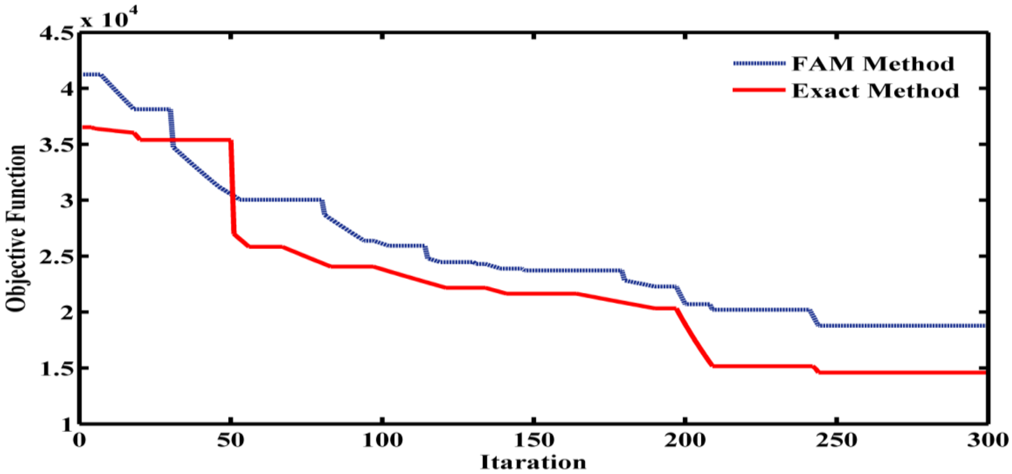

Figure 8: Convergence of the optimization process using FAM and exact methods for the barrel vault

As seen in Fig. 8, the optimization procedure using the exact method converged to a weight of nearly 17 tons, while the optimization using the FAM reached a weight of approximately 19 tons. Thus, the FAM-based optimization is considered a reasonable approximation of the exact method. Additionally, the optimization process using the FAM was significantly faster, taking about half the time of the exact method in Opensees.

3.3 Example 3: Double-Layer Grid with 200 Members

A double-layer grid with 200 members, with dimensions of 25×25 meters and a height of 2 meters, was evaluated using the FAM and SSOA for inelastic behavior and optimization, as shown in Fig. 9. This structure has 61 nodes, with nodes 7, 11, 51, and 55 supported at their base.

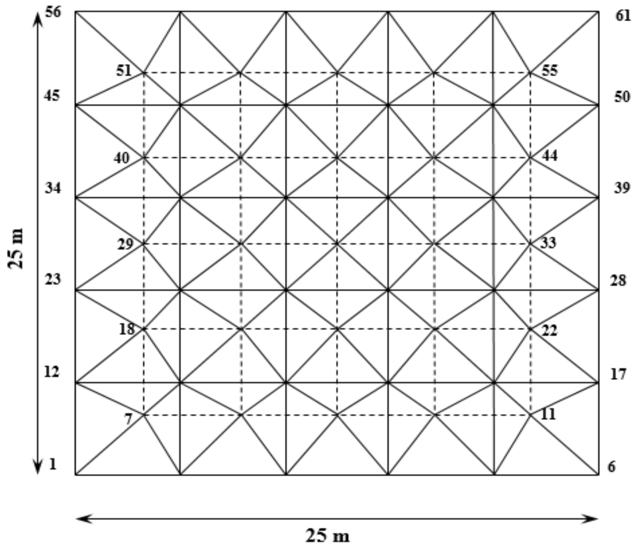

Figure 9: Schematic of the double-layer grid with 200 members

The members of the double-layer grid were classified into three groups: Group I consisted of the bottom members, Group II contained the top members, and Group III included all members in the layers between the upper and lower layers. The cross-sectional types for the optimization process are listed in Table 1. The modulus of elasticity and density of the members were 2.01×10^6 kg/cm^2 and 7850 kg/m^3, respectively. The grid structure was also subjected to the Kobe earthquake records, as shown in Fig. 4. The convergence behavior of the optimization process for both the FAM and exact methods is shown in Fig. 10.

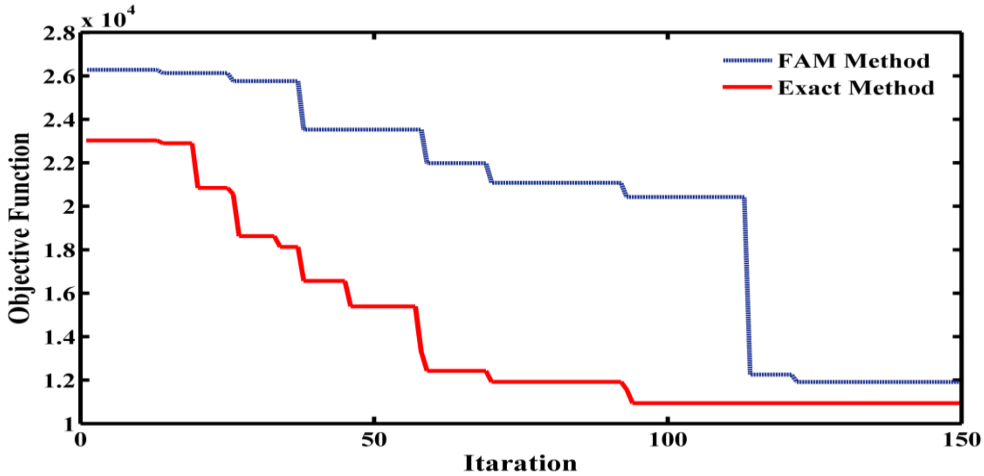

Figure 10: Convergence of the optimization process using FAM and exact methods for the double-layer grid

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As seen in Fig. 10, the exact method showed a more regular convergence pattern compared to the FAM. However, both methods converged to nearly the same optimal solution, with the FAM estimating an optimal weight of around 12 tons and the exact method yielding a result of about 11 tons. Furthermore, the optimization process using the FAM was significantly faster, requiring only 60% of the time taken by the exact method. Therefore, the FAM greatly accelerated the optimization process.

4. CONCLUSION

This study aimed to apply the Force Analogy Method (FAM) as an approximate technique for optimizing space structures in the inelastic region. Given the large search space and the time-consuming nature of nonlinear analysis, the FAM can significantly reduce computation time and speed up the optimization process. It accurately simulates the nonlinear behavior of space structures and produces reliable results while reducing the computational effort compared to traditional nonlinear analysis methods. In FAM, only the initial stiffness matrix of the structure is calculated once, and the state transition matrix remains unchanged throughout the analysis. This reduces computational time significantly, especially for large structures such as space structures. Therefore, the FAM proves to be an efficient tool for nonlinear analysis and optimization in large-scale structures. This study described the FAM method for structures with axial members, such as space structures, subjected to seismic forces. After validating the FAM's performance, it was used to optimize the weight of two space structures with 200 and 729 members using the SSOA algorithm. The results showed that the FAM reduces computation time significantly while providing optimization results that closely match the exact method. Thus, approximate methods like the FAM are highly recommended for optimizing large-scale space structures.

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REFERENCES

1. Lin TH. Theory of inelastic structures, *John wiley & Sons*, 1968.
2. Kaveh A. Applications of metaheuristic optimization algorithms in civil engineering, *Switzerland*: *Springer International Publishing*, 2017.
3. Kaveh A, Ghozaan MI. Meta-heuristic algorithms for optimal design of real-size structures, *Switzerland*: *Springer International Publishing*, 2018.
4. Kaveh A. Advances in metaheuristic algorithms for optimal design of structures, *Switzerland*: *Springer International Publishing*, 2014.
5. Wong KKF, Yang R. Inelastic dynamic response of structures using force analogy method, *J Eng Mech* 1999; **125**(10): 1190-1199. https://doi.org/10.1061/(ASCE)0733-9399(1999)125:10(1190)
6. Wong KKF, Wang Z. Seismic analysis of inelastic moment-resisting frames part I: modified force analogy method for end offsets, *Struct Design Tall Spec Build* 2007; **16**(3): 267-282. https://doi.org/10.1002/tal.314
7. Song S, Li G. Inelastic dynamic analysis of steel structure using force analogy method, *Appl Mech Mater* 2012; **166**: 304-309. https://doi.org/10.4028/www.scientific.net/AMM.166-169.304

8. Li G, Fahnestock LA, Li HN. Simulation of steel brace hysteretic response using the force analogy method, *J Struct Eng* 2013; **139**(4): 526-536. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000664
9. Li G, Zheng Y, Li HN. Seismic damage analysis of reinforced concrete frame using the force analogy method, *J Eng Mech* 2013; **139**(12): 1780-1789. https://doi.org/10.1061/(ASCE)EM.1943-7889.0000618
10. Li G, Zhang Y, Li HN. Nonlinear seismic analysis of reinforced concrete bridges using the force analogy method, *J Bridge Eng* 2015; **20**(10): 04014111. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000721
11. Safaei S, Taslimi A, Tehrani P. The application of the force analogy method (FAM) in pushover analysis for steel moment resisting frames, *8th international conference on seismology & earthquake engineering*, *Tehran*, *Iran*, 2019.
12. Bahar H, Bahar A. A force analogy method (FAM) assessment on different static condensation procedures for frames with full Rayleigh damping, *Struct Design Tall Spec Build* 2018; **27**(9): e1468. https://doi.org/10.1002/tal.1468
13. Kaveh A, Zaerreza A. Comparison of the graph-theoretical force method and displacement method for optimal design of frame structures, *Structures* 2022; **43**: 1145-1159. https://doi.org/10.1016/j.istruc.2022.07.035
14. Kaveh A, Rezazadeh Ardebili S. Optimum design of 3D reinforced concrete frames using IPGO algorithm, *Structures* 2023; **48**: 1848-1855. https://doi.org/10.1016/j.istruc.2023.01.071
15. Kaveh A, Shabani Rad A. Metaheuristic-based optimal design of truss structures using algebraic force method, *Structures* 2023; **50**: 1951-1964. https://doi.org/10.1016/j.istruc.2023.02.123
16. Li G, Wong K. Theory of nonlinear structural analysis: The force analogy method for earthquake engineering, John Wiley & Sons, 2014.
17. Dicleli M, Calik EE. Physical theory hysteretic model for steel braces, *J Struct Eng* 2008; **134**(7): 1215-1228. https://doi.org/10.1061/(ASCE)07339445(2008)134:7(121
18. Kaveh A, Biabani Hamedani K. Improved arithmetic optimization algorithm and its application to discrete structural optimization, *Structures* 2022; **35**: 748-764. https://doi.org/10.1016/j.istruc.2021.11.012
19. Kaveh A, Kalatjari VR, Talebpour MH, Torkamanzadeh J. Configuration optimization of trusses using a multi heuristic based search method, *Int J Optim Civil Eng* 2013, **3**(1): 151-178.
20. Talebpour MH, Abasabadarby Y. Optimization of steel frames with reliability constraint under the effect of fire load using colliding bodies optimization algorithm, *Int J Optim Civil Eng* 2021; **11**(4): 547-562.
21. Kaveh A and Zaerreza A. Shuffled shepherd optimization method: a new Meta-heuristic algorithm, *Engineering Computations*, 2020; **37**(7): 2357-2389. https://doi.org/10.1108/EC-10-2019-0481
22. Kaveh A, Hosseini SM and Zaerreza A. Improved shuffled jaya algorithm for sizing optimization of skeletal structures with discrete variables, *Structures* 2021; **29**(February): 107-128. https://doi.org/10.1016/j.istruc.2020.11.008

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