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Optimum Design of Structures for Seismic Loading by Simulated Annealing Using Wavelet Transform

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ABSTRACT

Optimization of earthquake-affected structures is one of the most widely used methods in structural engineering. In this paper optimum design of structures for earthquake loading was achieved by simulated annealing method. The evolutionary algorithm was employed for optimum design of two space structures. To reduce the computational work, a discrete wavelet transform (DWT) was used. In DWT the number of points in the earthquake record was decreased with Mallat Method. A dynamic analysis of time history was carried out. By DWT the earthquake signal was decomposed into a number of points. Then the two space structures were optimized for these reduce points. The actual responses were reconstructed with a reverse wavelet transform (RWT). A number of space structures were designed for minimum weight. The result show, DWT and RWT were an effective approach for reducing the computational cost of optimization.

1. Introduction

Many studies have been conducted about optimization in civil engineering [1,2]. Optimum design of structure was to select the design variables such that the weight of structure was

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minimized [3–7]. Optimization of earthquake-affected structures is one of the most widely used methods in structural engineering. The optimum design of structure for earthquake loads was formulated and the optimum value was obtained by simulated annealing [8]. During recent years, many studies have been conducted to design the structures under dynamic loading. Chang et. al developed a multi-purpose method based on genetic algorithm using fuzzy logic theories for the optimal design of two-dimensional frames subjected by dynamic loading [9]. In reference [10] PSO algorithm was used for optimum design of structures for dynamic loading. Kaveh and Talatahari [11–13] designed and optimized various types of structures, for which a charged system search algorithm was used.

In this work, member cross-section was considered as design variables. These members were chosen from a set of discrete variables. The constraints of optimization were used as bounds on member stresses and displacements joint of structures.

For large structures, the analysis was very time consuming, and the optimal process was very inefficient. A DWT was used to transfer the earthquake record to a signal with small number of points [14–16]. Thus, the dynamic analysis of structure was carried out with lesser points. One of the applications of wavelet transform is damage identification. Damage identification with wavelet packet was used by Naderpour and Fakharian [17].

The wavelet theory (WT) was the solution to overcome the shortcomings of the Fourier transform (FT) [18]. One of the applications of wavelets used in this paper was using a wavelet transform to produce an approximate earthquake record from the main earthquake record.

The dynamic analyses of structures for the main record were computed with RWT. The numerical results indicated that this method was a powerful technique. The value of error in this method was small. Salajegheh and Heidari decomposed the main record of earthquake into a new record with smaller point [6].

In the present study, the details of DWT and RWT will be explained. The details of optimization will be discussed. Some numerical examples will be presented. The computational time of optimization method was compared.

2. Simulated annealing

The basis of simulated annealing (SA) method was a random search algorithm for determining the minimum value by emulating the natural process found in metals during a temperature drop. The SA technique makes stochastic changes with a probabilistic acceptance criterion. The temperature started was chosen and reduced by a rate during the optimization. The algorithm accepts the random values of the search at the high temperatures, and then move drops at the low temperature. At temperature, T, the algorithm perturbs the position and evaluates the resulting change in the energy of the system. The most frequently used function in SA was as:

$$Pr = \frac{1}{1+e^{(O_A - O_C)/\theta}} \tag{1}$$

where θ indicates temperature, O_A and O_C represent the objective function for a candidate design and the current point, respectively. If $O_A \geq O_C$, was the criterion of accepting or rejecting new point. This point for optimization was selected and compared with *Pr,* value should be in the interval *(0,1)*. If the value was lower than *Pr*, the point will be accepted or rejected. In an optimization solution, θ was a control parameter which regulates the convergence of the method. For the cooling schedule the final temperature (θ_F), cooling factor (C_f), and choices of initial temperature (θ_s) was required. Cooling schedule formulations were used as follows [19,20]:

$$\theta_s = -\frac{1}{\ln(Pr_s)} \tag{2}$$

$$\theta_f = -\frac{1}{\ln(Pr_f)} \tag{3}$$

$$C_f = [\frac{\ln(Pr_s)}{\ln(Pr_f)}]^{1/(N_c-1)} \tag{4}$$

where N_c indicates the number of cooling cycles; Pr_s and Pr_f show the initial and final acceptance probabilities, respectively. The initial temperature was assigned such that the poor candidate designed at first was treated with an average Pr_s. The initial value of temperature was high for higher values of the starting acceptance probability. Therefore, it was mostly chosen as 0.5 to 0.9. In the some researchers consider, Pr_s=0.5 [19–21]. Acceptance probability was equated to small values for example $Pr_f = 10^{-7}$ or 10^{-8} in the final process. The cooling factor ($0<C_f<1$) applied for reducing the temperature. The cooling cycles number (N_c) was selected, and the temperature of the next cycle θ_{c+1} was calculated as $\theta_{c+1} = C_f\theta_c$, where $\theta_c$was the temperature of previous cycle. The decreasing temperature was very sensitive to the number of cooling cycles [21]. In references [19–21] it shows that for $N_c=100$, optimum design was found, and $N_c=200$ and 300 were suitable values.

3. Wavelet transform

The structures have been analyzed for seismic loadings by FT and FFT, which well used in dynamic analysis [22]. Wavelet transform (WT) was used as a mathematical tool in signal processing [23].

4. DWT of earthquake record

In DWT, filters with different frequencies are used for analyzing signals in different scales. By passing the signal through high- and low-pass filters, the different signals are analyzed. In discrete conditions, the signal resolution is controlled by filter operators and the scale varies using down-sampling or up-sampling. DWT of signal was defined as follows [23]:

$$\mathrm{DWT}(\tau,s)=\sum_{t=0}^{N-1} a(t)\psi^*[\frac{(t-\tau)\delta t}{s}] \tag{5}$$

This equation is a function of two variables a and b. Here b indicates translation, a represents scale and is corresponding to period. Index * shows complex conjugate, s and ψ are the main wave (earthquake record) and mother wavelet, respectively and δt indicates the time increment. ψ was defined as:

$$\psi\left[\frac{(t-\tau)\delta t}{s}\right]=\left(\frac{\delta t}{s}\right)^{0.5}\psi_0\left[\frac{(t-\tau)\delta t}{s}\right] \tag{6}$$

in which ψ_0 was called mother wavelet. In this study, Morlet function [24] was used as follows:

$$\psi_0(t)=e^{i\omega_0 t}e^{-t^2/2} \tag{7}$$

An appropriate value for ω_0 can be considered as ω_0=6. The smallest value for s_0 was as $s_0=b\delta t$, where $b>1$. The larger scales were chosen as power of two multiples s_0.

5. RWT of responses

The WT was a reversible, and the main signal can be reconstructed by the following equation:

$$a(t)=c_\psi\sum_j\sum_k DWT(\tau_k,s_j)\psi\left(\frac{(t-\tau_k)\delta t}{s_j}\right) \tag{8}$$

where c_ψ was a constant value, which should be satisfy the following condition:

$$c_\psi=2\pi\int_{-\infty}^{+\infty}\frac{|\hat{\psi}(\omega)|^2}{|\omega|}d\omega<\infty \tag{9}$$

where $\hat{\psi}(\omega)$ was Fourier transform of $\psi(t)$.

6. The main steps of optimization with DWT and RWT

The main steps of optimization method with DWT and RWT were as:

1. A mother wavelet (Eq. 7) was chosen.
2. A minimum scale of s_0, and the all other scales were chosen.
3. The location of the first wavelet τ was considered equal to zero.
4. Specifying scale and translation was determined according to Eq. 6.
5. Equation 5 was used to determine the DWT of the main earthquake record.
6. The value of τ parameter was increased, and the process was repeated from step 4.
7. The procedure was repeated until τ to be the end point of the main earthquake record.
8. DWT coefficients were computed.
9. DWT coefficients were new records. The dynamic responses of the investigated structure were considered for these points using Newmark method [23].
10. Using Eq. 8 the actual responses were reconstructed
11. Using SA method, the structure was optimized.
12. Check the convergence of the optimization, if convergence was satisfied, the process will be stopped, otherwise the cross-sections will be updated and the process was repeated from step 8.

7. Two numerical examples of truss

Two space structures were optimized. The ElCentro S-E 1940 earthquake record is used. The response of dynamic analysis of the structure was calculated by the Newmark method. The earthquake record was applied only in *x* direction. The optimization was carried out by the SA using exact dynamic analysis (SAE), and SA using DWT and RWT (SAW) method. In all the examples, modules of Elasticity was 2.1×10^6 kg/cm^2, weight density was equal to 0.0078 kg/cm^3, damping ratio was considered 0.05, allowable stress was taken 1100 kg/cm^2, members were pipes, with radius to thickness less than 50cm.

7.1. Example number 1

A space structure with double layer grid shown in Fig. 1 was optimized. The dimensions of 10×10m for top layer and 8×8m for bottom layer was used. The height of the structure was 0.5m. At the corner joints 25, 21, 5 and 1 of the bottom-layer simply supported was used. At each free node of truss the mass of 3 kg.s^2/cm was lumped. The vertical displacement of joint 13 must be lower than 10cm. A set of available values for the cross-sectional areas of the members was given in Table 1. The members were categorized into 13 different types and shown in Table 2. The convergence history of optimization was given in Fig. 2 and Table 3. In the cases SAE and SAW, the number of generations were 287 and 256, the final weights were 5397.7 and 5372.2 kg, and the time was 53 and 9 minute, respectively.

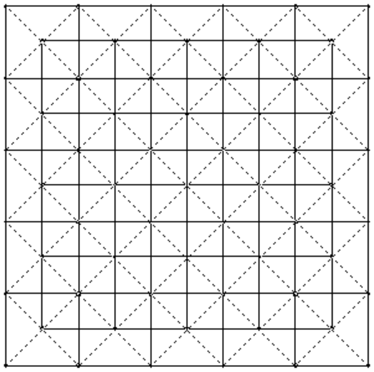

Fig. 1-a. the plan of space structure.

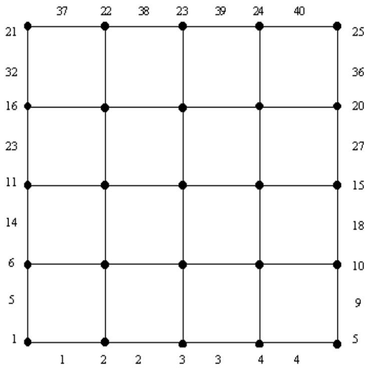

Fig. 1-b. Bottom layer of space structure.

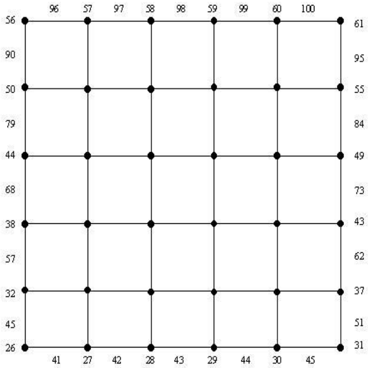

Fig. 1-c. Top layer of space structure.

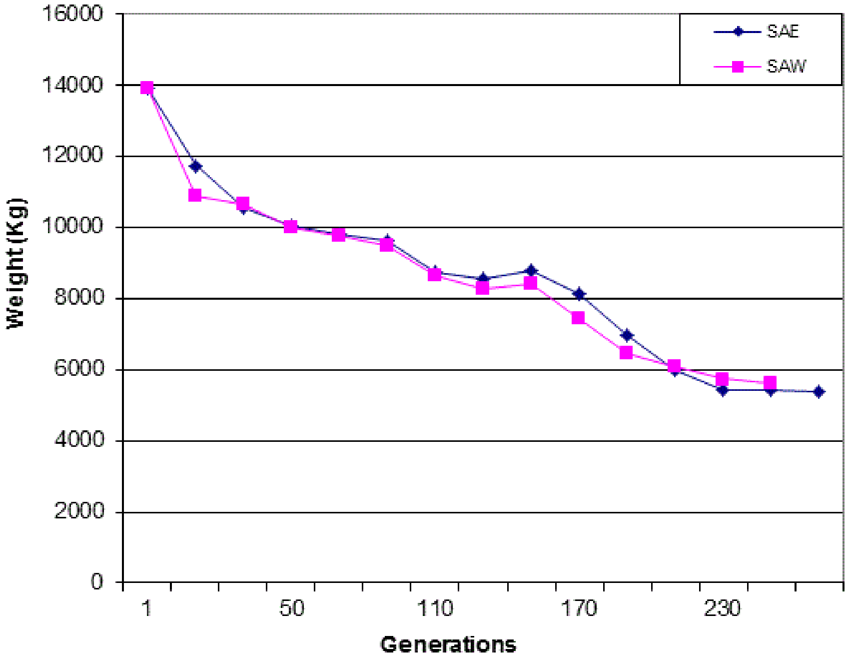

Fig. 2. Convergence history with SA.

Table 1
Available Member Areas (cm^2).

No.	Area	No.	Area	No.	Area	No.	Area
1	0.8272	9	3.789	17	12.99	25	27.54
2	1.127	10	4.303	18	13.66	26	29.69
3	1.727	11	4.479	19	15.11	27	33.93
4	2.267	12	5.693	20	17.13	28	40.14
5	2.777	13	6.563	21	18.74	29	43.02
6	3.267	14	7.413	22	19.15	30	51.03
7	3.493	15	8.229	23	21.15	31	68.35
8	3.789	16	9.029	24	25.11	32	70.7

Table 2
Member Groups.

No.	Member	No.	Member	No.	Member
1	1-4; 37-40	6	7; 16; 25; 34	11	47; 50; 58; 61; 69; 72; 80; 83; 91; 94
2	10-13; 28-31	7	41-45; 96-100	12	48; 49; 59; 60; 70; 71; 81; 82; 92; 93
3	19-22	8	52-56; 85-89	13	Diagonal members
4	5; 9; 14; 18; 23; 27; 32; 36	9	63-67; 74-78		
5	6; 8; 15; 17; 24; 26; 33; 35	10	46; 51; 57; 62; 68; 73; 79; 84; 90; 95		

Table 3
Results of Optimization.

Group no.	**Areas (cm^2)**	
	SAE	**SAW**
1	68.35	68.35
2	10.57	10.57
3	3.789	3.789
4	10.57	10.57
5	10.57	10.57
6	18.74	18.74
7	12.99	10.57
8	12.99	12.99
9	10.57	9.029
10	12.99	10.57
11	4.479	3.789
12	18.74	18.74
13	25.11	25.11
Weight (kg)	5397.7	5372.2
Generation no.	287	256
Time (min.)	53	9

7.2. Example number 2

The space truss shown in Fig. 3 was optimized. The mass of 6 $kg.s^2/cm$ was lumped at each node of truss. The problem was optimized with stress, horizontal displacement and Euler's buckling constraints. The horizontal displacement was considered to be lesser than 8cm. A set of discrete values considered for the member cross-section areas were given in Table 1. The category of members was shown in Table 4.

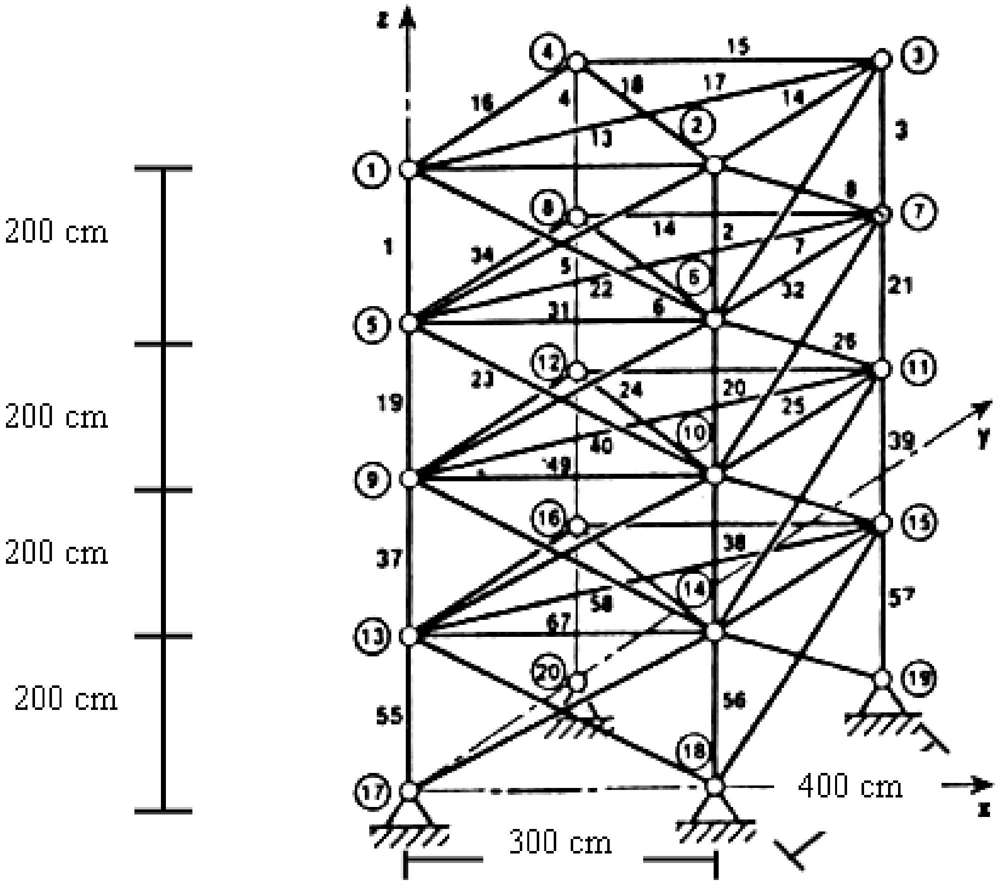

Fig. 3. Space structure of example 2.

The optimization results and converge history were given in Table 5 and Fig. 4, respectively. In the cases SAE and SAW, the generation numbers were 218 and 187, the final weights 1372.1 and 1357.7kg, and the time of computation were 28 and 5 minute, respectively.

Table 4
Member Groups.

No.	Member	No.	Member
1	1, 2, 3, 4, 5, 6	7	37, 38, 39, 40, 41, 42
2	7, 8, 9, 10, 11, 12	8	43, 44, 45, 46, 47, 48
3	13, 14, 15, 16, 17, 18	9	49, 50, 51, 52, 53, 54
4	19, 20, 21, 22, 23, 24	10	55, 56, 57, 58, 59, 60
5	25, 26, 27, 28, 29, 30	11	61, 62, 63, 64, 65, 66
6	31, 32, 33, 34, 35, 36	12	67, 68, 69, 70, 71, 72

Table 5
Results of Optimization for Example 2.

Group no.	**Areas (cm^2)**	
	SAE	**SAW**
1	0.8272	0.8272
2	1.127	1.127
3	1.727	1.727
4	2.777	3.267
5	10.57	10.57
6	13.66	12.99
7	21.15	19.15
8	27.54	25.11
9	8.229	8.229
10	10.57	10.57
11	10.57	10.57
12	10.57	10.57
Weight (kg)	1372.1	1357.7
Generation no.	218	187
Time (min.)	28	5

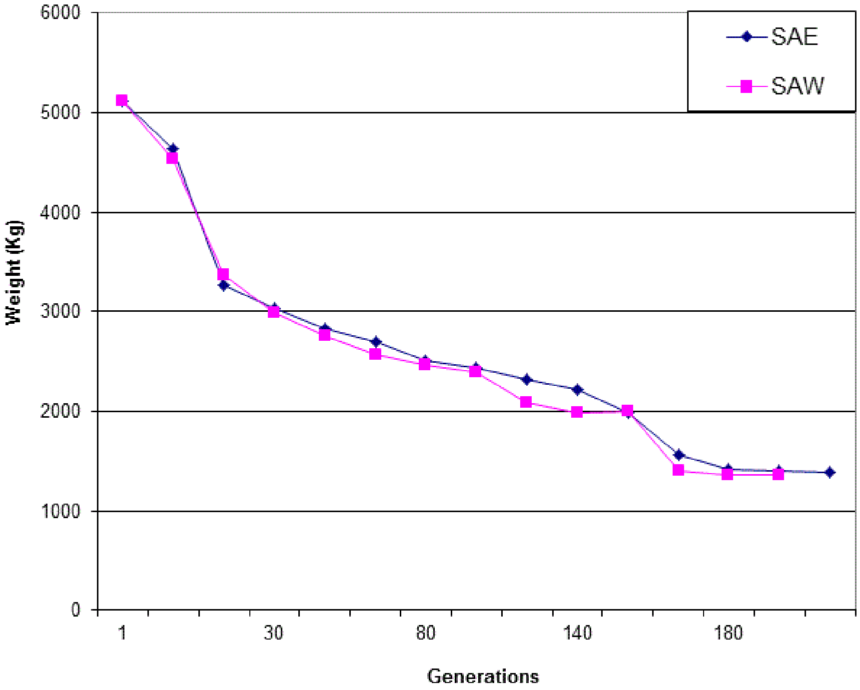

Fig. 4. History of convergence for example 2 with SA.

8. Conclusions

In this paper, optimum design of structures for seismic loading was obtained by SA method. DWT was used to reduce the computational time. The earthquake record was decomposed into a number of points using DWT and the structures were analyzed for these reduced points. Two space trusses were designed. From the two example, the following results can be driven:

(a) The iteration histories show that SA converges uniformly.
(b) The value of objective function in SAW was lesser than SAE.
(c) DWT and RWT were an effective approach for reducing the computational cost of optimization.
(d) In SAW method the execution time is reduced and the maximum error is negligible.

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