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Research Paper

Optimum location belt truss system and pattern recognition with neural network based on belt truss system

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Abstract

Belt truss systems have gained significant traction in the past two decades for their effectiveness in mitigating lateral loads caused by wind and earthquakes in tall buildings. This research investigates the structural behavior of belt trusses in high-rise buildings, focusing on their potential to reduce lateral displacement through movement and energy dissipation. The study complements the existing body of research by employing a neural network (NN) for the optimal placement of belt truss structures. The investigation analyzes two steel frame structures, a 30-story and a 40-story building, incorporating belt truss systems. Through displacement and weight balance analysis, the optimal location for the belt truss in each structure is identified. Furthermore, a pattern recognition-based neural network is developed using input and target functions derived from structural analysis software. This NN offers a computationally efficient alternative for analyzing the vast number of potential configurations (approximately 1,400 states) for these high-dimensional structures with belt trusses. Compared to traditional software, the proposed NN approach has the potential to deliver more accurate results, including optimal truss location, weight, and movement targets, within a significantly reduced timeframe. The research is structured in two sections: the first section explores the belt truss system and its impact on structural behavior, while the second section delves into the development and application of the neural network system. These sections work synergistically to provide a comprehensive approach to optimizing belt truss placement in high-rise buildings.

Keywords: Belt truss system; Target function; Input functions; Neural network; Optimum weight; Displacement.

1. Introduction

All buildings prevalent today around the world are a result of increasing research, development, and innovation in the field of civil engineering. They are subjected not only to gravity loads but also to significant amounts of lateral loads caused by severe ground motions, strong winds, and other environmental loading. Efficient structural systems are being designed to transfer all of these loads safely to the ground (Ali and Moon [1]). Since the effects of earthquake and wind loads increase with the height of a building, significant consideration of lateral loads is more important for taller structures (Halder and Dutta [2]). Preliminary design of tall buildings is the initial step in the design process. When designing tall buildings, conceptual design, preliminary design, preliminary analysis of structure, detailed design, final design, and detailing of structures are all conducted to complete the total design process (Lützkendorf and Lorenz [3]). Preliminary building design is defined as the selection and proportioning of the most suitable and appropriate structural components, such as beams, columns, slabs, foundations, and bracing systems (Taranath [4]). In the initial design stage, the known values of some key building design and response parameters are very useful pieces of information for selecting the most appropriate size of structural components.

The ever-increasing height of buildings presents unique challenges and opportunities for the construction industry. Two critical aspects of tall building design are controlling lateral displacement and minimizing base moments within the core structure. The belt truss system has emerged as a promising technique to achieve these goals. In a belt truss system, the central core, typically a steel shear wall or braced frame, acts as a rigid anchor. Cantilever arms extend from the core to connect with the peripheral columns of the building, significantly reducing overall structural deflection [5]. Extensive research has explored the potential of belt trusses. Studies have addressed the optimal design of bracing systems for multi-story steel frames, the placement of single and paired belt trusses, and the effectiveness of du



al belt truss configurations at specific building heights [6]. In high-rise buildings, strengthened stories are floors with outriggers connecting the concrete core wall with the perimeter columns. A "high-rise structural system with an energy-dissipating story" is a structural system that uses energy-dissipating technology proposed by various researchers [7]. In this system, steel braces in the strengthened stories are replaced by energy-dissipating braces. The dampers in the energy-dissipating braces dissipate the earthquake energy imparted to the structure, reduce the dynamic response of the structure, and help preserve the integrity of the main structure. This type of structural system allows for more possibilities for using buckling-restrained braces (BRBs) in high-rise buildings. BRBs have been integrated into buildings in the US, Canada, China, and New Zealand and have gained popularity in the construction sector [8], such as in buckling-restrained braced frames and retrofit civil structures. Extensive research has been conducted on the performance of BRBs [9-12]. In high-rise buildings, strengthened stories are floors with outriggers connecting the core wall with the perimeter columns. A "high-rise structural system with an energy-dissipating story" is a structural system that utilizes energy-dissipating technology, as proposed in [13].

Artificial neural networks, fuzzy logic, rich picture approach, analytical hierarchy process, and hybrid mixed approaches are some of the emerging techniques and applications of artificial intelligence used for preliminary tall building design, optimization of structural components, and selection of proper structural systems (Adeli [14]). Proportioning structural systems using knowledge-based expert systems, which are usually implemented by complex computer programs, are trained to use a knowledge base to solve real-life problems. This is a very useful technique for increasing accuracy during the preliminary design phase (Poon [15]). Different branches of artificial intelligence, such as knowledge-based expert systems, linear optimization, genetic algorithms, and artificial neural network tools, can be used for the preliminary design of tall buildings (Cohn and Dinovitzer [16]). An artificial neural network is an information processing system consisting of massively large parallel connections. It is a mathematical model designed for input-output mapping, which achieves perceptual tasks, recognition tasks, and mimics the behavior of the human brain (Al Shamisi et al. [17]).

This research aims to investigate the potential of using artificial neural networks to optimize the design and performance of belt truss systems in tall buildings.

2. Core and Belt Truss System

Despite the widespread adoption of belt bracing systems in recent decades, their origins can be traced back much further, particularly in the context of tall buildings. Similar to the use of cantilever anchors to counteract wind loads on ship sails, belt trusses function as external supports in these structures. By connecting the core to peripheral columns, they transform bending moments within the core into horizontal shear forces distributed across the columns. The optimal placement of belt trusses varies depending on the building's height. For a single belt truss, architectural constraints may favor positioning it at the highest story. However, from a purely structural standpoint, minimizing displacement dictates placement at the mid-height level. Figure 2 illustrates how the overturning moment in the core is translated into a vertical couple acting on the exterior columns. Floor diaphragms located at the top and bottom of the belt trusses offer resistance to core rotation. Consequently, a portion of the core moment is converted into a horizontal couple within these floors (Figure 2a). This horizontal couple, transferred through the two floors to the chords of the truss, is then transformed by the truss itself into vertical forces acting on the exterior columns (Figure 2b).

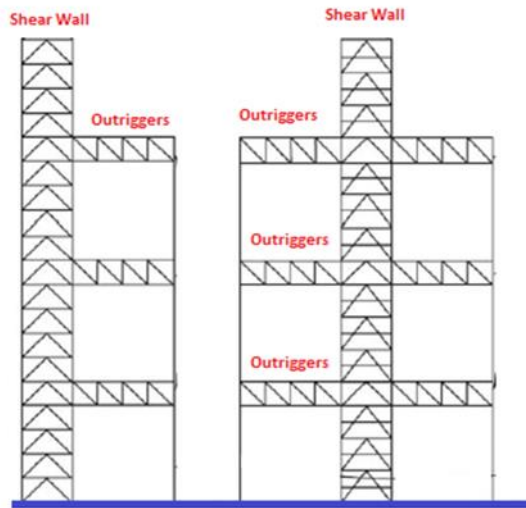


Fig. 1. Belt and core structural truss system

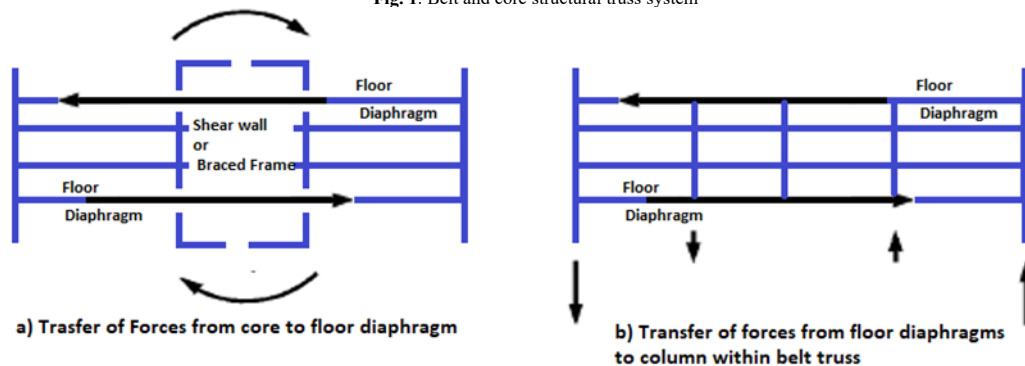


Fig. 2. Force transfer belt truss as virtual outrigger

3. Structural modeling

This study investigates two symmetrical high-rise building models with 30 and 40 stories, respectively. Both models have a regular plan dimension of 25 meters



by 25 meters, divided into five equal spans of 5 meters each. A constant story height of 3.5 meters is assumed. ETABS 2013 software was employed for structural analysis, adhering to all relevant engineering principles and established criteria. The governing design code used is AISC-ASD-89. Live and dead loads were assigned as 200 kg/m² and 600 kg/m², respectively. W-sections were chosen for both beams and columns. The localization of the belt truss system was determined using established formulas proposed by Smith and Salim (1983) [3]. The specific formulas will be presented in a subsequent section.

$$\left\{ \begin{array}{ll} 0.25 < \frac{X_1}{H} < 0.5 & \text{Single truss} \\ 0.2 < \frac{X_1}{H} < 0.35 \text{ } \text{ } \text{ } 0.45 < \frac{X_2}{H} < 0.7 & \text{Dual truss} \\ 0.17 < \frac{X_1}{H} < 0.25 \text{ } \text{ } 0.4 < \frac{X_2}{H} < 0.55 \text{ } \text{ } 0.55 < \frac{X_3}{H} < 0.25 & \text{Triple truss} \end{array} \right. \quad (1)$$

In this study, the total height of the structure is denoted by H. The distances of the locations of the first, second, and third belt trusses from the roof side are denoted by X₁, X₂, and X₃, respectively.

4. Type of paper the 30 and 40-Story frames results

Following the design phase, finite element analysis software, ETABS, was employed to extract key performance parameters, including optimal weight, relative displacement, and roof movement. Subsequently, weight-roof displacement and weight-relative displacement balance diagrams were generated to establish the relationships between these critical design considerations.

Table 1. Structure weight, relative displacement, and roof displacement for 30-story structure

s30	Number floor and situation belt trusses	Relative displacement (max disp...)	Roof displacement	Total weight
1	30-16	.004216	.003091	19401.6475
2	30-18	.004968	.003737	19613.4236
3	30-20	.0042296	.003569	19639.0508
4	30-22	.0046214	.003264	19715.12633
5	30-30	.004182	.003077	19622.8776
6	30-10-20	.003931	.003352	19048.8068
7	30-10-21	.004122	.003576	19003.7348
8	30-10-22	.004312	.003773	18931.9748
9	30-10-24	.0050971	.003887	19288.9976
10	30-12-20	.004133	.003178	19130.2462
11	30-12-21	.004165	.003010	19017.2573
12	30-12-22	.004312	.003115	18931.9748
13	30-12-23	.005412	.004859	18947.3985
14	30-12-24	.005226	.003915	19325.1721
15	30-14-20	.004923	.004168	19368.4053
16	30-14-23	.004993	.004295	19024.9045
17	30-14-24	.0051041	.003845	19445.5534
18	30-15-22	.0050502	.004238	18811.0619
19	30-16-20	.005135	.0041583	19471.74957
20	30-16-22	.0049223	.004033	19495.36533
21	30-16-24	.0047	.003905	18867.1261
23	30-29-30	.004547	.003935	19261.8881
24	30-8-15-24	.00453	.00337	18643.0734
25	30-8-16-24	.00488	.004127	18640.3449
26	30-8-17-24	.00531	.004576	18484.484
27	30-8-18-24	.005162	.004344	18576.5816
28	30-10-15-24	.004912	.004113	18641.9534
29	30-10-16-24	.005111	.004455	18907.4025
30	30-10-18-24	.004318	.003279	18976.187
31	30-12-15-24	.004715	.003929	18934.6089
32	30-12-17-24	.0041	.003755	19941.6743
33	30-12-18-24	.0051568	.0038534	19243.1189
34	30-14-16-24	.0049708	.003896	18379.45201
35	30-14-17-24	.0046633	.0038523	19369.7292
36	30-14-18-24	.0042116	.003782	19367.6778
37	30-14-19-24	.0041288	.00373	19362.32002
38	30-28-29-30	.00413	.003830	19188.065
39	30-6-12-18-30	.00452	.003719	20393.942
40	30-8-16-24-30	.004985	.003919	18543.625
41	30-10-18-24-30	.004393	.003849	18903.1462



42	30-10-19-24-30	.004151	.0038	18977.4429
43	30-12-18-24-30	.0049	.003655	19018.2039
44	30-27-28-29-30	.004952	.003174	19037.7175

Table 2. Structure weight, relative displacement, and roof displacement for 40 story structures

S40	Number floors and situation belt trusses	Relative displacement (max disp.)	Roof displacement	Total weight
1	40-26	.003995	.003209	27229.94725
2	40-27	.003899	.003510	27174.58252
3	40-28	.004158	.003416	27119.7032
4	40-29	.004928	.003781	26981.5436
5	40-30	.004877	.003917	26998.9124
6	40-14-26	.004235	.003543	26982.10684
7	40-14-28	.004876	.003571	26857.54402
8	40-14-29	.004710	.003807	26848.26934
9	40-14-30	.004634	.003703	26894.07953
10	40-14-32	.004882	.003463	26986.7886
11	40-15-28	.004522	.003686	26821.11252
12	40-16-26	.004221	.003634	26938.30234
13	40-16-27	.004667	.003382	26898.48027
14	40-16-29	.004829	.003965	26807.02063
15	40-16-32	.004503	.003495	26958.36897
16	40-17-27	.004677	.003418	26874.62
17	40-17-30	.004887	.003862	26797.0595
18	40-18-26	.004267	.003658	26924.04117
19	40-18-28	.004965	.004160	26694.5926
20	40-18-30	.004852	.003872	26774.6333
21	40-20-26	.004401	.003319	26877.4554
22	40-20-28	.004664	.004199	26681.9863
23	40-20-30	.0046	.003553	26599.2682
24	40-20-32	.004554	.003745	26632.5844
25	40-21-28	.005054	.004249	27036.45
26	40-21-29	.004878	.004128	26709.94396
27	40-22-26	.004617	.003429	26787.80133
28	40-22-28	.004779	.004283	26655.2236
29	40-22-30	.004716	.003903	27425.2649
30	40-22-32	.004759	.003661	26874.54103
31	40-39-40	.004864	.004470	27159.05375
32	40-10-20-32	.004367	.003717	26781.1589
33	40-10-22-33	.004443	.003747	26779.51906
34	40-10-24-32	.004492	.003902	26681.20068
35	40-11-22-33	.004305	.003739	26774.35803
36	40-11-20-32	.004840	.003696	26772.03302
37	40-12-20-32	.004852	.003719	26753.70997
38	40-12-22-32	.004932	.003801	26749.1468
39	40-13-20-32	.004934	.003721	26753.94399
40	40-13-23-32	.004864	.003765	27653.94399
41	40-14-21-32	.004472	.003768	26764.96064
42	40-14-24-32	.004629	.003149	26664.77031
43	40-15-20-32	.004860	.00374	26742.1603
44	40-15-23-32	.004563	.003961	26700.84545
45	40-16-19-32	.004372	.003714	26716.78345
46	40-16-22-32	.004605	.004003	26688.2848
47	40-16-24-32	.004231	.003861	27148.04373
48	40-38-39-40	.004426	.003877	27111.60003
49	40-8-20-30-40	.004415	.003526	26663.6069
50	40-8-22-32-40	.004856	.003338	26746.6778
51	40-10-20-30-40	.004846	.003532	26669.12313
52	40-10-22-30-40	.004843	.004424	26682.03407
53	40-12-22-30-40	.004743	.00359	26662.2094
54	40-12-22-32-40	.004878	.003357	26713.4249
55	40-14-20-28-40	.004691	.003742	26521.7242
56	40-14-22-28-40	.005041	.004282	27067.75315
57	40-14-18-32-40	.004821	.003690	27241.23562
58	40-37-38-39-40	.004556	.003982	27114.807

5. Analytical Results

An analysis of Figures 3 and 4 was conducted to identify feasible space and optimal locations for belt trusses in a 30-story structure. Based on the weight-displacement balance depicted in Figure 3, three optimal configurations for belt truss placement were identified. These configurations correspond to states 6, 24, and 34. In the dual and triple truss configurations, optimal placement varies depending on the specific state. For the dual truss configuration, optimal placement occurs at the 10th and 20th stories (state 6), while the triple truss configuration benefits from placement at the 8th, 15th, and 24th stories (state 34) or the 14th, 16th, and 24th stories (state 24). Notably, state 6 exhibits the lowest displacement but at the expense of a higher weight compared to state 34.



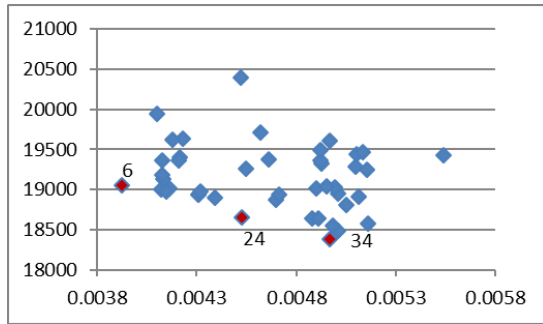


Fig. 3. Equilibration space of target functions of weight-relative displacement in 30-story

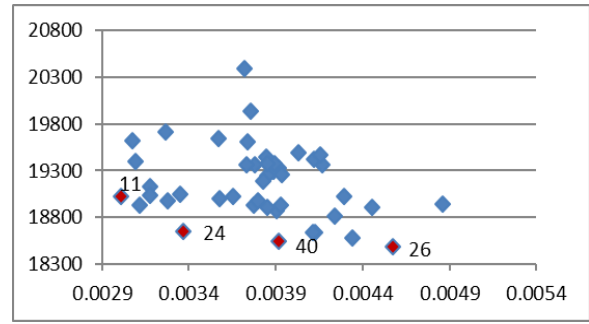


Fig. 4. Equilibration space of target functions of weight-roof displacement in 30-story

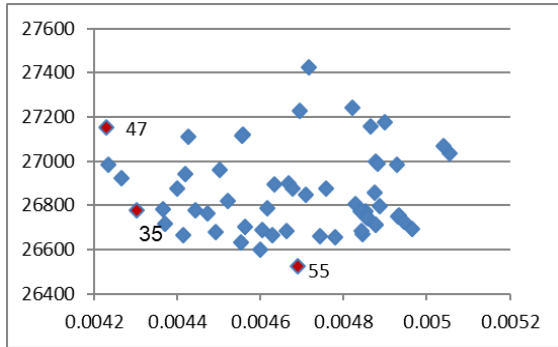


Fig. 5. Equilibration space of target functions of weight-relative displacement in 40-story

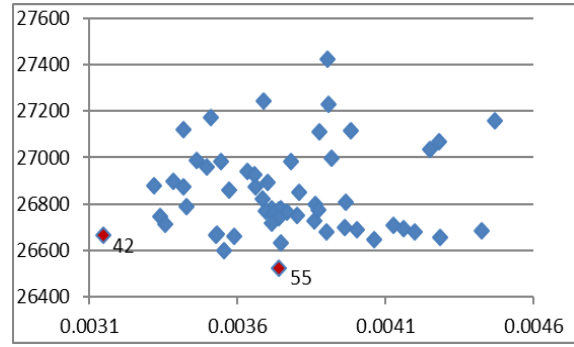


Fig. 6. Equilibration space of target functions of weight-roof displacement in 40-story

Fig. 6. Equilibration space of target functions of weight-roof displacement in 40-story

Figure 4 presents the target function space for weight and roof displacement. This space is confined to four distinct states: 11, 24, 26, and 40. Consequently, dual-, triple-, and tetraploid truss configurations can achieve optimal states within this structure. The optimal location for the dual truss state is identified within stories 12-21. Two optimal locations are observed for the triple truss state: stories 8-15-24 and 8-17-24. These locations exhibit minimal displacement variation. The optimal location for the tetraploid truss state is found in stories 8-16-24-30. The dual truss state exhibits the minimum overall movement. However, within the triple truss state, stories 8-17-24 represent a co-optimal location with both low weight and low displacement characteristics. Figures 3 and 4 depict the sets of balanced solutions for the target function of weight and relative displacement in the 40-story structure. Analysis of Figure 3 reveals that states 35, 47, and 55 represent the most optimal points. In this configuration, both triple and tetraploid truss states are achievable. The optimal locations for the belt trusses in the triplet state are stories 16-24-32 and 11-22-33, while the optimal location in the tetraploid state is stories 14-20-28-40. Notably, the optimal number of trusses in this state is either 3 or 4. Figure 4 shows the balanced solutions for the target function of weight and roof displacement. Based on this figure, states 42 and 55 are identified as optimal. While the triple truss in state 42 exhibits optimal placement within stories 14-24-32, resulting in lower displacement, the tetraploid truss in state 55 achieves optimality in stories 14-20-28-40, albeit with a higher weight. A table summarizing the obtained optimal stories based on structure height, with comparisons for triple and tetraploid states, is presented for further analysis (data not shown).

Table 3. Evaluation of location of optimum triple belt truss based on the coefficient of structure height

	First Truss	Second Truss	Third Truss
Number 24 for structure 30	0.267	0.5	0.8
Number 42 for structure 40	0.35	0.6	0.8
Number 35 for structure 40	0.275	0.55	0.82

Table 4. Evaluation location of optimum tetraploid belt truss based on coefficient of structure height

	First Belt Truss	Second Belt Truss	Third Belt Truss	Fourth Belt Truss
Number 40 for structure 30	0.267	0.533	0.8	1
Number 55 for structure 40	0.35	0.5	0.7	1



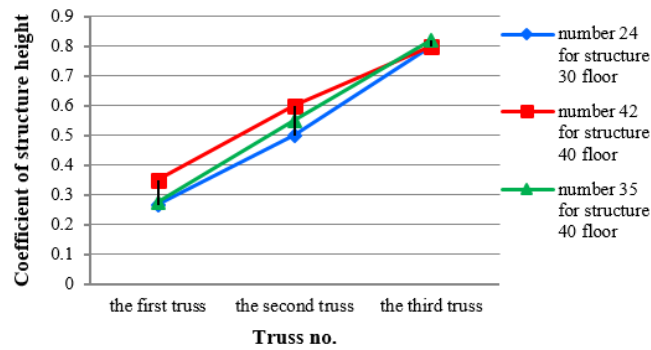


Fig. 7. Comparison of optimum states of triple truss based on coefficient of structure height for both states (D-DR)

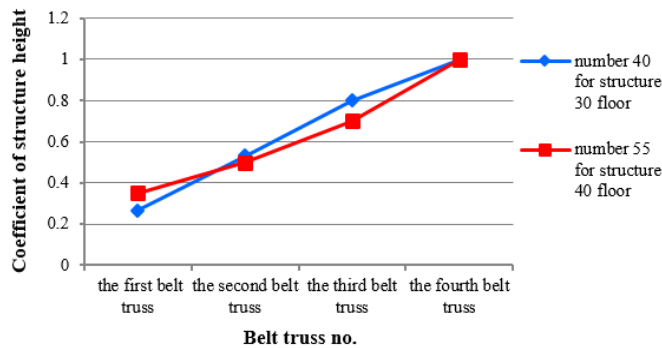


Fig. 8. Comparison of optimum states of Tetraploid truss based on the coefficient of structure height for both states (D-DR)

An analysis of comparison diagrams revealed that for the belt truss in the triplet state, the optimal placements were found to be at distances of 0.3, 0.5, and 0.8 of the structure's height. In the tetraploid state, one belt truss was positioned at the top stories, while the remaining three were placed at distances of 0.3, 0.5, and 0.8 of the structure's height. (Note: D refers to displacement structure and DR refers to roof displacement).

6. Type of Paper Performance Process with Neural Network

Artificial Neural Networks (ANNs) or Neural Networks (NNs) have emerged as an exciting alternative method for tackling a wide range of problems across various scientific and engineering disciplines. Inspired by the information processing capabilities of biological nervous systems, ANNs leverage data to learn and acquire knowledge. The fundamental principle underlying inadequately trained neural networks was first presented by Hebb in 1949 [13].

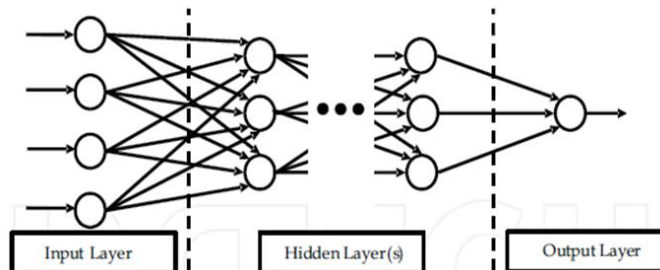


Fig. 9. Schematic figure of the neural network

The mechanisms by which individual neurons organize and arrays of neurons adapt their behavior to external stimuli remain an active area of research, with much still unknown beyond the well-established principles of single-neuron function. This ongoing investigation is reflected in the broad variety of experimental neural network structures currently employed. Here, we focus solely on describing the structure, mathematical underpinnings, and resulting behavior of the backpropagation network. This choice is motivated by its prevalence and generality as the most widely used neural network architecture.

A MATLAB-based neural network was designed for pattern recognition using input and target functions. The network was trained on 44 models of 30-story buildings and 58 models of 40-story buildings. The input functions included floor number, location of the first truss (I), locations of trusses II, III, and IV, and building height. The target functions consisted of relative displacement, roof displacement, and total weight of the structure. The location of belt trusses was specified as an input parameter in the MATLAB software. For structures with a single belt truss compared to those with four, a value of zero was used in the neural network software to represent the absence of additional trusses. In this way, the network could handle two data sets—'input' and 'target'—with dimensions of 102×6 and 102×3, respectively (based on the 30- and 40-story models).



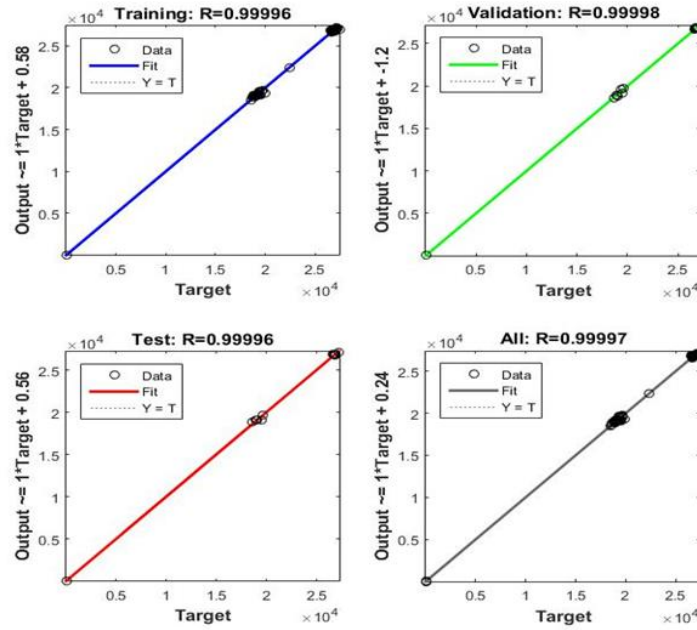


Fig. 10. Regression Neural Network Based Education

As illustrated in Figure 10, network training exhibited a curvilinear relationship with test performance and validation of results. The green point on the diagram represents the inflection point. The blue line signifies the training trend based on the data. The green line indicates the evaluation of the network's training validity, and the red line depicts the tested results against the target functions [15].

The structure regression analysis followed the aforementioned procedure based on the training of input functions. The training function was established according to the validation training of target functions using software that achieved a total error rate of 0.99996, effectively equal to 1. Subsequently, samples obtained from ETABS software were analyzed, and the results from the neural network were compared to these samples. The error rate between the network outputs and the ETABS data was then calculated.

Table 5. Results of selected structures

Number floor and situation of belt truss	Relative displacement	Roof displacement	Total weight
30-10-21	.004122	.003576	19003.7348
30-8-17-24	.004512	.003676	18484.484
30-14-17-24	.0046633	.0038523	19369.7292
40-20-30	.0046	.003553	26599.2682
40-10-22-33	.004492	.003902	26681.20068
40-12-22-30-40	.004743	.00359	26662.2094

Samples were then processed based on story number, location of belt truss, and structure height using a neural network implemented in MATLAB. In the following section, we present two examples with numerical results and analysis from the neural network for structures with dimensions 31-10-21 and 30-8-17-24.

Table 6. Results of selected structures based on neural network

Number floor and situation of belt truss	Relative displacement	Roof displacement	Total weight
30-10-21	0.0040522	0.0033489	19002
30-8-17-24	0.0045091	0.0037556	18842
30-14-17-24	0.0045832	0.003794	19127
40-20-30	0.0047112	0.0035017	26776
40-10-22-33	0.004518	0.004029	26708
40-12-22-30-40	0.004837	0.0036596	26850

The influence of input data quantity on network performance was investigated. It was observed that increasing the number of training data points led to a more accurate and optimal target function. This aligns with previous research suggesting that fully defining network structure and target functions enhances generalizability [16]. A comparison between ETABS and the neural network software revealed minimal percentage differences in drift, roof displacement, and total weight values. All aforementioned parameters were employed for this comparative analysis.



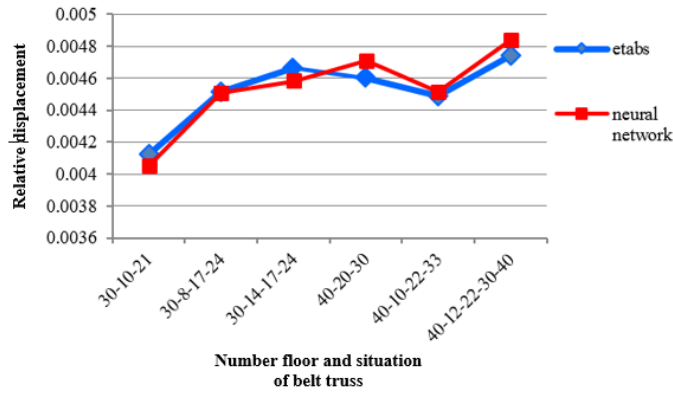


Fig. 11. Charts comparing the relative displacement for both CASE (ETABS-ANN)

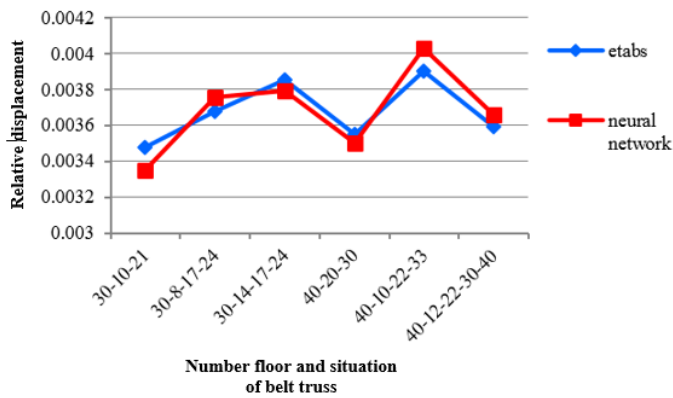


Fig. 12. Charts comparing the roof displacement for both case (ETABS-ANN)

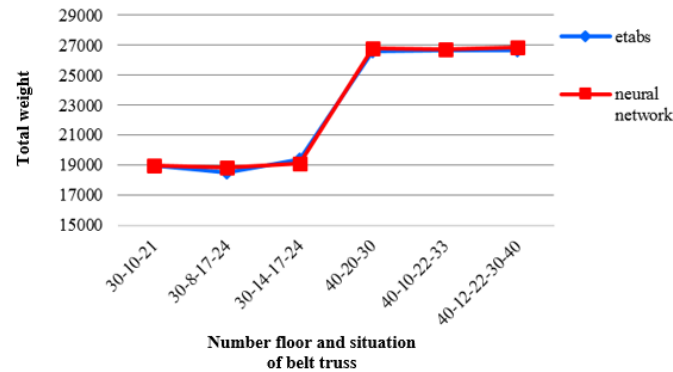


Fig. 13. Charts comparing the total weight for both case (ETABS-ANN)

7. Conclusions


Model-based optimization was conducted on 30- and 40-story structures. For the dual truss system, the optimal locations for the belt trusses were identified at normalized heights of 0.333 and 0.667 (distance divided by structure height). For the triple truss system (based on Figure 5), optimal locations were found at normalized heights of 0.3, 0.5, and 0.8. Similarly, for the tetraploid truss system, one belt truss was optimally placed on the top floor, with the remaining three located at normalized heights of 0.3, 0.5, and 0.8. While a vast number of potential belt truss configurations exist for 30- to 40-story structures (potentially hundreds of thousands), a network requiring only a limited number of structural analyses was successfully established. This network, based on essential functions, achieved minimal error rates with just six model analyses and a subset neural network implementation. Notably, significant variations in relative and roof displacements were observed in the diagrams; however, these variations were attributed to the small overall displacement values, and no significant differences in total weight were observed among the optimal configurations. In today's emphasis on speed, efficiency, and cost-effectiveness, this research offers significant advantages. Conventional structural analysis software (e.g., ETABS, Opensys) can require several hours per model, leading to substantial time and cost investments. In contrast, the proposed neural network approach facilitates the evaluation of hundreds of models within minutes.





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