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# MULTI-OBJECTIVE OPTIMAL NUMBER AND LOCATION FOR STEEL OUTRIGGER-BELT TRUSS SYSTEM

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**Abstract**

During the past two decades, outrigger-belt truss system has been investigated and used in design of tall buildings. Most of the studies focused on the optimization of the system for minimum displacement and some of them proposed the best locations. In this study, however, multi-objective optimization of tall steel frames with belt trusses is investigated to minimize displacement and weight of the structure. For this purpose, structures with 20, 30, 40, and 50 stories are considered as models, based on the suggestions in the literature. The location and number of trusses and cross section of all structural elements are considered as design variables. After sizing of the structure for a specific topology and shape, weight and displacement of the structure are obtained and plotted in a diagram to illustrate trade-off between two objective functions. The results show the optimal Pareto-front solutions for different stories. Smooth trade-off and optimal number of trusses and their locations obtained.

Keywords: Outrigger-belt truss, Steel structures, Tall buildings, Weight, Displacement, Optimization, Pareto-front.

## 1. Introduction

Need for tall buildings in the world are growing fast and although development of the high-rise structures began from the late 19$^{th}$ century and the United States was pioneer, but today these structures are constructed and some are under construction in Asia, e.g. Malaysia, Singapore, China, and Hong Kong.

Earthquake loads and wind loads are so important in design of tall buildings and these loads create large displacements and vibrations. Outrigger-belt truss system is one of appropriate systems to control the responses. In this system, core bears shear force and outrigger-trusses with external columns provides resistance against overturning moment and controls displacements. Location and number of

## Nomenclatures

| | |
|---|---|
| $E$ | Young's modulus, kg/cm$^2$ |
| $H$ | Total height of the structure, m |
| $X_1$ | Distance of the first truss from the roof, m |
| $X_2$ | Distance of the second truss from the roof , m |
| $X_3$ | Distance of the third truss from the roof, m |

**Abbreviations**

| | |
|---|---|
| 2D | Two Dimensional |
| 3D | Three Dimensional |
| ASCE | American Society of Civil Engineers |
| CA | Cellular Automata |
| DL | Dead Load, kg/m$^2$ |
| ETABS | Extended Three-dimensional Analysis of Building Systems |
| IMRF | Intermediate Moment Resisting Frames |
| LL | Live Load, kg/m$^2$ |
| OC | Optimality Criteria |

trusses in this system are the challenging issues and many studies carried out to optimize this system. Smith and Salim [1] formulated optimum drift resistance of outrigger- trusses with different number of trusses and proposed optimum location for belt trusses. In their study, drift was the only objective function.

There are many methods developed for optimal design of structures and the most popular algorithms are heuristic algorithms. Bianca et al. studied to optimize built truss system using genetic algorithm [2]. In another work, multi-objective optimization of steel moment resisting frames is studied using a novel algorithm and interesting results obtained [3]. Optimization of continuum structures using cellular automata (CA) algorithm developed and modified and better results reported in the literature [4].

Liang et al. [5] studied optimal topology for steel framed belt trusses. Chan and Wong [6] studied to find optimal topology and size of steel tall braced frames using OC-GA algorithm. Early study on belt truss system was parametric study to formulate optimum drift [7]. Researchers in the literature have developed mathematical and approximate methods for optimal design of belt truss [8-10]. Taranath [8] proposed optimum location for single and double-truss. Optimum positioning for trusses is studied and reported in the previous research works [11-12]. Tomšil and Duhovnik [13] applied evolutionary structural optimization with regard to commonly used topologies for simultaneous topology and size optimization of 2D and 3D trusses.

Bayati et al. [14] optimized multi-outriggers to stiffen the system. Wu and Lee [15] evaluated structural performance of this system under uniform and triangular lateral loads. Lee and Kim [16] proposed a simplified analytical model for outrigger-braced structures considering transverse shear deformation. Some researchers assumed this system as cantilever beam [7] and modelled the system by a torsional spring [8]. Recently, Babaei et al. [17] investigated some examples of outrigger-belt trusses for exploring optimal location for trusses.

In this article, however, optimal design of belt truss system is carried out without heuristic algorithms, and instead numerous design models are evaluated to find optimal solutions. In other words, topology optimization is performed using parametric study by considering different models, while size optimization is carried out using the software option. Weight and drift/displacement are employed as objective functions; therefore, objective space and Pareto-front for solutions are obtained for structures with different storey numbers.

Although there is a limit for displacement by the design codes no drift or displacement constraints have been applied, since displacement is one of the objective functions in this article. In multi-objective optimization problems the objective function could not be the constraint at a same time.

## 2. Method and numerical models

### 2.1. Methodology

In this study, many steel frame models with different number and different locations of belt trusses are considered to be analyzed and designed. Linear analysis is performed. Each model is analyzed by ETABS and then designed according to the latest code [18]. Using the auto select capabilities of the software, best cross sections are obtained after some iteration. In the other words, for a given topology and shape, optimal sizes are obtained.

### 2.2. Property and geometry of the models

Figure 1 displays the plan and dimensions of the models and possible locations for the belt trusses in the plan. Figure 2 illustrates a 20-storey model with two outrigger trusses at the $11^{th}$ and $20^{th}$ stories. The span width is 6 meter and the height of all stories is 3.5 meter. The structure's elements are assumed to be intermediate moment resisting frames (IMRF).

In total, 248 design models with different number and different location for belt trusses are analyzed and designed. Among them, 13 models of 20-story, 51 models of 30-story, 80 models of 40-story, and 104 models of 50-story are considered for evaluation. Belt truss numbers are vary from one to four, and the locations are distributed through the height of the building, as discussed in the next section.

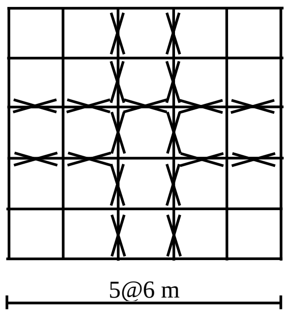


**Fig. 1. Plan of the models.**

A uniform dead of DL = 600 kg/m$^2$ and live load of LL = 200 kg/m$^2$ are assumed. Earthquake loads are calculated based on the ASCE 7-10 [19]. The seismic zone is Tehran city (seismology risk is very high) and all national code requirements are applied. Calculation of the earthquake loads, however, is carried out using the American standard [19], using the ETABS software options. A planner frame containing outrigger truss is taken to evaluate and gravity and lateral loads are distributed through the frames based on their bearing spans and rigidity. In other words, 3D symmetric frames are converted to 2D frames and analysis and design processes are performed.

Structural steel is used for all the structural members including columns, beams, and belt trusses. A value of 2100000 kg/cm$^2$ is considered for the Young's modulus. The yield stress is set 2400 kg/cm$^2$ and the ultimate tensile strength is assumed to be 3600 kg/cm$^2$.

## 2.3. Topologies

Since the number of possible locations for trusses are too much and it is impossible to evaluate each feasible topologies, a limit number of topologies based on the suggestions in the literature are considered to be investigated, which is different for models.

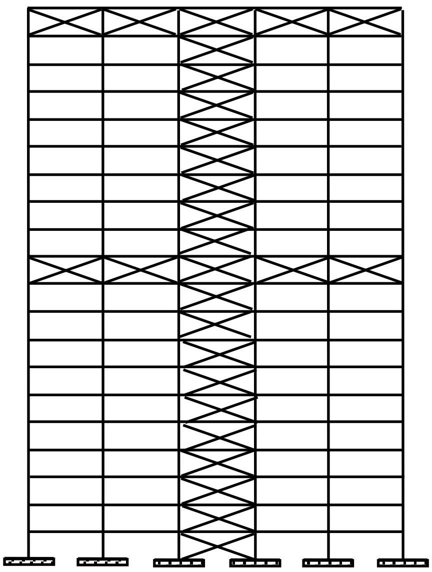

**Fig. 2. Topology of a 20-storey model with core and outrigger belt trusses.**

Smith and Salim studied outrigger belt-truss system, formulated the system and evaluated different locations with different number of trusses [1]. In their study, only single objective function, maximum displacement, was considered and a number range is proposed for optimum designs.

In this study, the proposed range in the literature Smith and Salim [1, 7] is used to reduce the number of possible topologies. For instance, when using single truss the proposed location is as Eq. (1).

$$0.25 < \frac{X_1}{H} < 0.5 \quad (1)$$

For two trusses, the best locations are shown in Eq. (2) and Eq. (3).

$$0.2 < \frac{X_1}{H} < 0.35 \quad (2)$$

$$0.45 < \frac{X_2}{H} < 0.7 \quad (3)$$

The optimal locations for three trusses are presented in Eq. (3), Eq. (4), and Eq. (5), respectively.

$$0.17 < \frac{X_1}{H} < 0.25 \quad (4)$$

$$0.4 < \frac{X_2}{H} < 0.55 \quad (5)$$

$$0.55 < \frac{X_3}{H} < 0.8 \quad (6)$$

where, H is the total height of the structure; $X_1$, $X_2$, and $X_3$ are the distance of the first, second and the third truss from the roof, respectively, if there are.

Table 1 displays the number and storey locations of the trusses for 20-storey structures, which used as models. In all models, except 20-storey models, four trusses are also considered to evaluate optimal locations. Tables 2 to 4 display the number and storey locations of the trusses for models with 30, 40, and 50-storeies.

**Table 1. Number and storey locations of the trusses for the 20-storey models.**

| **Cases** | **Stories** | | |
|---|---|---|---|
| **Single Truss** | 11th to 17th | | |
| **Two Trusses** | 7th to 12th | | 14th to 17th |
| **Three Trusses** | 5th to 9th | 10th to 13th | 16th or 17th |

**Table 2. Number and storey locations of the trusses for the 30-storey models.**

| **Cases** | **Stories** | | | |
|---|---|---|---|---|
| **Single Truss** | 16th to 30th | | | |
| **Two Trusses** | 10th to 19th | | 21th to 30th | |
| **Three Trusses** | 8th to 18th | 15th to 19th | 24th to 30th | |
| **Four Trusses** | 6th to 12th | 12th to 18th | 18th to 24th | 24th to 30th |

**Table 3. Number and storey locations of the trusses for the 40-storey models.**

| **Cases** | **Stories** | | | |
|---|---|---|---|---|
| **Single Truss** | 21th to 30th | | | |
| **Two Trusses** | 12th to 22th | | 26th to 32th | |
| **Three Trusses** | 10th to 18th | 20th to 24th | 32th to 34th | |
| **Four Trusses** | 8th to 14th | 16th to 22th | 24th to 28th | 34th to 40th |

**Table 4. Number and storey locations of the trusses for the 50-storey models.**

| Cases | Stories | | | |
|---|---|---|---|---|
| **Single Truss** | $26^{th}$ to $38^{th}$ | | | |
| **Two Trusses** | $15^{th}$ to $28^{th}$ | | $33^{th}$ to $40^{th}$ | |
| **Three Trusses** | $12^{th}$ to $22^{th}$ | $24^{th}$ to $30^{th}$ | $40^{th}$ to $42^{th}$ | |
| **Four Trusses** | $10^{th}$ to $16^{th}$ | $18^{th}$ to $26^{th}$ | $28^{th}$ to $34^{th}$ | $42^{th}$ to $44^{th}$ |

## 3. Results and discussion

The topologies, maximum drift and displacement, and the minimum weight of the specified layout for the 20-storey models are summarized in Table 5.

**Table 5. 20-storey models layout and design results.**

| Models | Truss locations | Drift | Roof Displacement (cm) | Weight (Ton) |
|---|---|---|---|---|
| **1** | **12** | 0.003747 | 34.2 | 289.87 |
| **2** | **14** | 0.004024 | 33.2 | 295.66 |
| **3** | **16** | 0.003943 | 33.2 | 303.36 |
| **4** | **8-14** | 0.003952 | 32.6 | 326.01 |
| **5** | **10-14** | 0.004038 | 32.4 | 322.69 |
| **6** | **12-14** | 0.003711 | 31.3 | 357.26 |
| **7** | **8-16** | 0.004174 | 31.5 | 369.7 |
| **8** | **10-16** | 0.003955 | 31.4 | 374.52 |
| **9** | **12-16** | 0.003743 | 30.8 | 382.2 |
| **10** | **6-10-16** | 0.004636 | 31.8 | 439.41 |
| **11** | **8-10-16** | 0.004396 | 31.2 | 433.91 |
| **12** | **6-12-16** | 0.004501 | 30.7 | 460.96 |
| **13** | **8-12-16** | 0.004302 | 31.3 | 435.38 |

Figure 3 displays trade-offs between weight and maximum storey drifts based on the design results for the 20-storey models, while Fig. 4 displays trade-offs between weight and roof displacement for these models. As shown in Fig. 3, all models are dominated by the models 1 and 6. In the other words, one truss at the $12^{th}$ storey or two trusses in the $12^{th}$ and $14^{th}$ stories are optimum for 20-storey structures, which are the Pareto-front solutions.

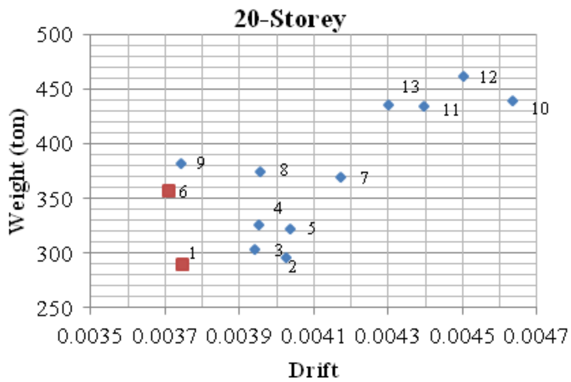


**Fig. 3. Trade-offs between weight and drift of 20-storey models.**

Where displacement and weight are objective functions, Pareto solutions are more smooth and meaningful. In this case, the optimum number of trusses could be one to three, where six Pareto solutions are obtained models 1, 2, 5, 6, 9, and 12.

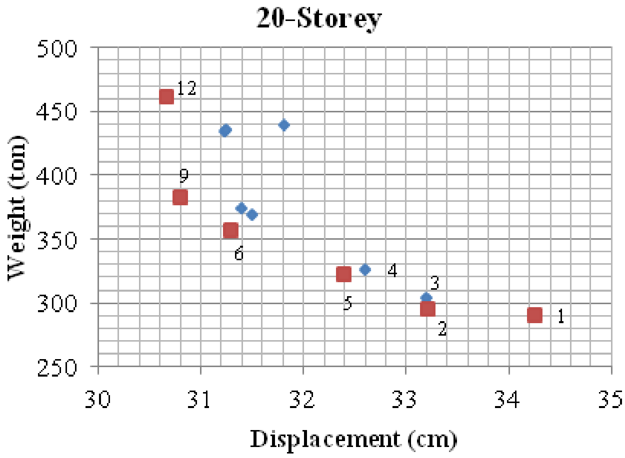


**Fig. 4. Trade-offs between weight and displacement of 20-storey models.**

The minimum weight is obtained (289.87 ton) where only one truss is needed at the 12$^{th}$ storey. The minimum displacement (30.7 cm) is obtained where three trusses at the 6$^{th}$, 12$^{th}$ and 16$^{th}$ stories are needed, which is similar to what proposed in the literature [7]. Other solutions, however, are obtained considering the weight objective function and there are significant differences in optimal number and location for trusses.

Table 6 displays the optimal number and optimal location for Pareto-front solutions obtained for 20-storey models. As is shown in this Table, where weight function versus displacement becomes more important the number of trusses decreases and vice versa.

Figures 5 to 10 illustrate design space for objective functions and optimal Pareto-front solutions and Tables 7 to 9 display models and optimal truss locations for 30, 40 and 50-storey models.

**Table 6. 20-storey optimal Pareto-front results.**

| Models | Truss locations | Roof Displacement (cm) | Weight (Ton) |
|---|---|---|---|
| 1 | 12 | 34.2 | 289.87 |
| 2 | 14 | 33.2 | 295.66 |
| 5 | 10-14 | 32.4 | 322.69 |
| 6 | 12-14 | 31.3 | 357.26 |
| 9 | 12-16 | 30.8 | 382.2 |
| 12 | 6-12-16 | 30.7 | 460.96 |

As shown in Fig. 6 and Table 7, the optimum number of trusses could be three or four and the best locations are shown. Figure 11 displays optimal moment resisting frame structures with minimum weight where no trusses are located.

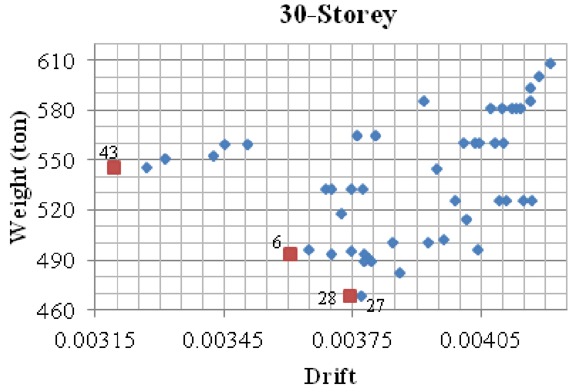


**Fig. 5. Trade-offs between weight and drift of 30-storey models.**

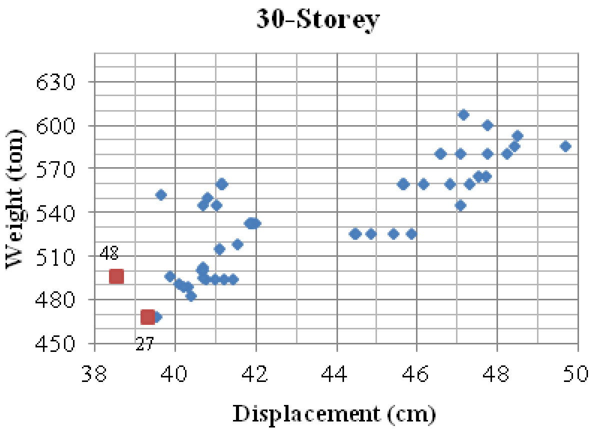


**Fig. 6. Trade-offs between weight and displacement of 30-storey models.**

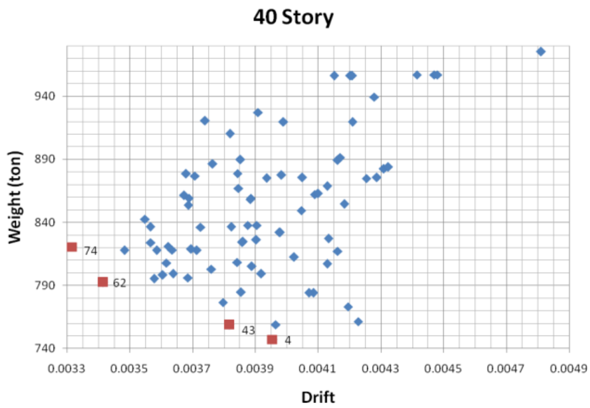


**Fig. 7. Trade-offs between weight and drift of 40-storey models.**

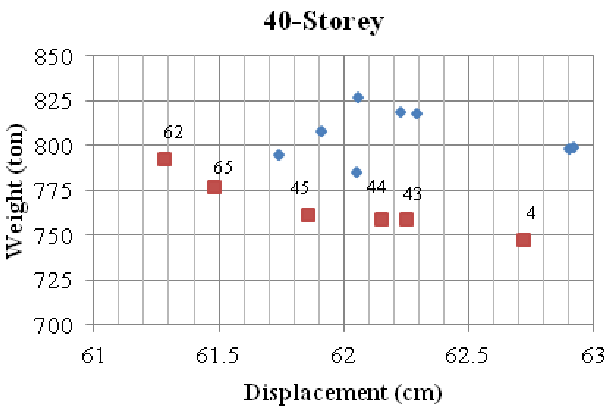


**Fig. 8. Trade-offs between weight and displacement of 40-storey models.**

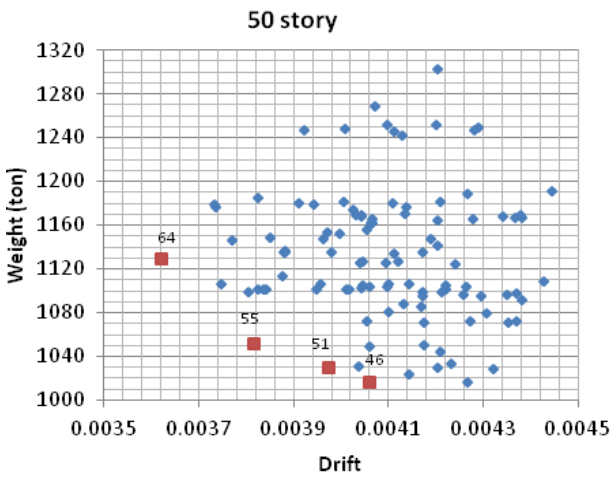


**Fig. 9. Trade-offs between weight and drift of 50-storey models.**

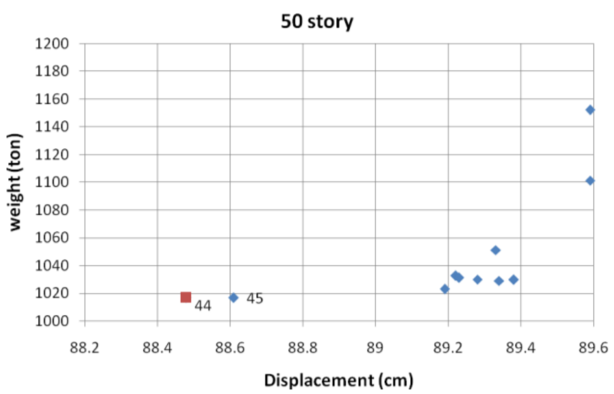


**Fig. 10. Trade-offs between weight and displacement of 50-storey models.**

**Table 7. 30-storey optimal Pareto-front models.**

| Models | Truss locations | Roof Displacement (cm) | Weight (Ton) |
|---|---|---|---|
| 27 | 8-15-24 | 39.32 | 468.08 |
| 48 | 6-12-18-24 | 38.515 | 496.32 |

**Table 8. 40-storey optimal Pareto-front models.**

| Models | Truss locations | Roof Displacement (cm) | Weight (Ton) |
|---|---|---|---|
| 4 | 12-20-32 | 62.7 | 746.94 |
| 43 | 10-16-24-34 | 62.2 | 758.46 |
| 44 | 10-16-26-34 | 62.1 | 758.77 |
| 45 | 10-16-28-34 | 61.9 | 761.21 |
| 62 | 12-20-26-34 | 61.3 | 792.44 |
| 65 | 12-22-26-34 | 61.5 | 776.42 |

**Table 9. 50-storey optimal Pareto-front models.**

| Models | Truss locations | Drift | Weight (Ton) |
|---|---|---|---|
| 46 | 12-18-30-42 | 0.00406 | 1016.79 |
| 51 | 12-20-32-42 | 0.00397 | 1029.97 |
| 55 | 12-22-32-42 | 0.00381 | 1051.34 |
| 64 | 12-26-34-42 | 0.00362 | 1128.73 |

Trade-off between two objectives of weight and maximum roof displacements are shown in Fig. 11 for models with different story numbers. This illustration implies that the slope for buildings with high story numbers trends to be flat which means that the core and outrigger belt truss system does not appropriate for taller buildings. In general, this system is proper for buildings including 20 up to 40 stories and for taller structures the maximum roof displacement increases largely and it is not allowed by the design codes. In this case there needs more trusses to control the structural responses and will affect on the weight and consequently on the structural cost.

Figures 12 through 15 display the obtained optimal topologies for the 20, 30, 40, and 50-storey models considering the total weight as the objective function. In other words, these topologies are the first solution in the Pareto-front curve, while the displacement objective function is ignored. As shown in these figures, for 20-storey model only one belt truss is needed at the 12$^{th}$ storey, for 30 and 40-storey models three belt trusses are obtained at different levels. Four belt trusses, however, are obtained for 50-storey model which should be located at the12th, 18th, 30th, and 42nd levels.

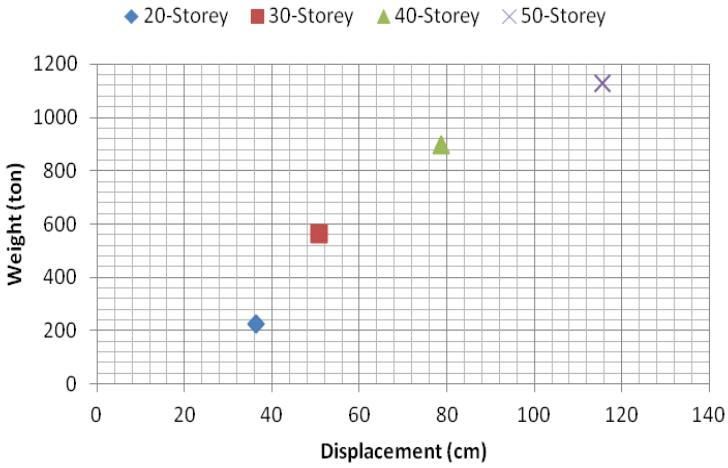


**Fig. 11. Trade-offs between objectives for models with different stories.**

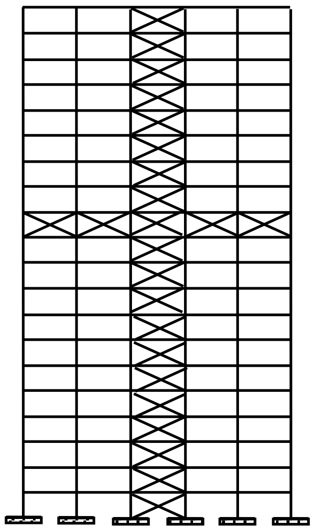

**Fig. 12. Optimal topology of the 20-storey model for weight objective function.**

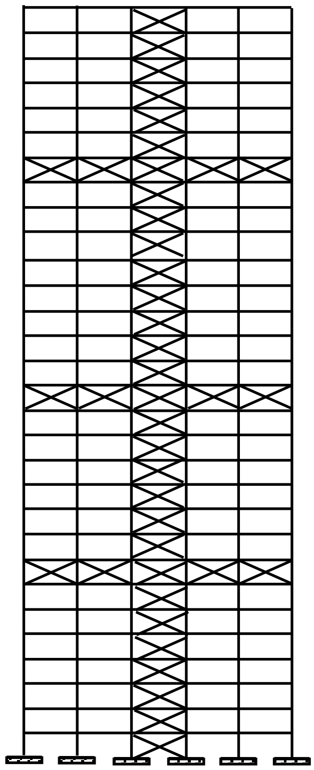

**Fig. 13. Optimal topology of the 30-storey model for weight objective**

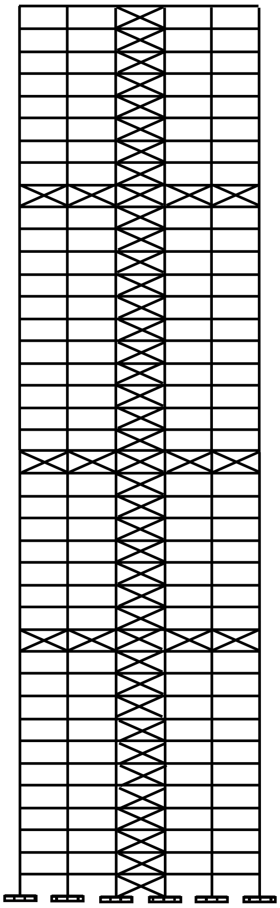

**Fig. 14. Optimal topology of the 40-storey model for weight objective function.**

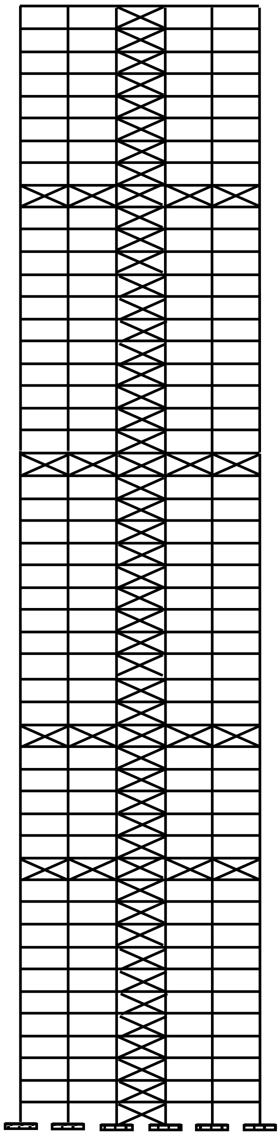

**Fig. 15. Optimal topology of the 50-storey model for weight objective function**

## 4. Conclusions

In this article, tall steel structures with core and outrigger belt-truss system of 20 to 50 stories are investigated to explore optimal number and location for trusses. Pareto-front optimal solutions in the design space for two objective functions (drift/displacement and weight) are obtained. In general, one to four trusses are obtained as optimal number for weight and displacement/drift optimization of 20 to 50-storey buildings, as follows.

In 20-storey structures, optimal number includes one, two or three trusses. Optimal weight obtained if one truss employed at the 12th storey, while for optimal displacement it needs three trusses at the 6th, 12th, and 16th stories. In 30-storey models, however, optimal solutions include three or four trusses. Trusses at the 8th, 15th, and 24th stories lead to optimal weight, while four trusses at the 6th, 12th, 18th, and 24th provides optimal roof displacement.

In 40-storey four trusses are needed to optimize displacement at the 12th, 20th, 26th, and 34th stories, and three trusses are obtained for optimal weight at the 12th, 20th, and 32nd stories. In 50-storey models, four trusses at the 12th, 18th, 30th, and 42nd stories and at the 12th, 26th, 34th, and 42nd stories are needed for optimal weight and optimal drift, respectively.

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