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Optimal Wind Bracing Systems for Multi-Storey Steel Buildings

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ABSTRACT: The major concern in the design of the multi-storey buildings is the structure to have enough lateral stability to resist wind forces. There are different ways to limit the lateral drift. First method is to use unbraced frame with moment resisting connections. Second one is to use braced frames with moment resisting connections. Third one is to use pin-jointed connections instead of moment-resisting one and using bracings. Finally braced frame with both moment-resisting and pin-jointed connections is a solution. There are lots of bracing models and the designer should choose the appropriate one. This thesis investigates optimal lateral bracing systems in steel structures. The method selects appropriate sections for beams, columns and bracings, from a given steel section set, and obtains a design with least weight. After obtaining the best designs in case of weight, cost analysis of all structures are carried out so that the most economical model is found. For this purpose evolution strategies optimization method is used which is a member of the evolutionary algorithms search techniques. First optimum design of steel frames is introduced in the thesis. Then evolution strategies technique is explained. This is followed by some information about design loads and bracing systems are given. It is continued by the cost analysis of the models. Finally numerical examples are presented. Optimum designs of three different structures, comprising twelve different bracing models, are carried out. The calculations are carried out by a computer program (OPTSTEEL) which is recently developed to achieve size optimization design of skeletal structures.

KEYWORDS: Optimization, Structural Optimization, Evolutionary Algorithms, Evolution Strategies, Steel Frames, Optimal Bracing Systems.

I. INTRODUCTION

The major concern in the design of multi-storey buildings is the lateral stiffness because it is the parameter that controls the lateral drift in the buildings. The lateral stiffness of a building is controlled by different structural systems. These are:

- Using unbraced frame with moment-resisting connections.
- Using braced frame with moment-resisting connections.
- Using braced frame with pin-jointed connections.
- Using braced frame with both moment-resisting and pin-jointed connections at the same time.



Figure 1.1 Bracing

There are lots of possible bracing models. The designer should consider all possible bracing types before deciding. Bracing can be in x-type, v-type, k-type, knee-type, z-type.

Since there are lots of possibilities of bracings and connections, choosing the appropriate one and minimizing the structure cost is the major concern in the design of steel buildings.

The main reason for choosing the wind forces as the main source of lateral force is that the most severe damages in multi-storey steel structures are caused by winds. For example, in the United States between 1986 and 1993, hurricanes and tornadoes caused \$41 billion in insured catastrophic losses, compared with \$6.18 billion for all other natural hazards combined (Taranath, Wind and Earthquake Resistant Buildings, 2005).

The optimization process is carried by a method called evolution strategies, which is a member of the evolutionary algorithms search techniques. Evolution strategies were developed in the early 1960s by Rechenberg and Schwefel, who were working at the Technical University of Berlin on an application concerning shape optimization (Eiben & Smith, 1998).

II. LITERATURE REVIEW

Another publication related with this topic is Memari & Madhkhan (1999), which deals with the optimization of structures under seismic. Allowable stress design of two-dimensional braced and unbraced steel frames based on AISC specifications subject to gravity and seismic lateral forces is formulated as a structural optimization problem. The objective function is the weight of the structure, and behavior constraints include combined bending and axial stress, shear stress, buckling, slenderness and drift. Cross-sectional areas are used as design variables. Among the specific observations resulting from the examples given in this study is insight with respect to the superiority of the K-braces over the other types in a minimum weight design sense.

One publication is Kameshki & Saka (2001), which uses genetic algorithm for the optimum design of bracing. In this study, the serviceability and stress constraints given in BS 5950 (1990) is used. The algorithm is used to design tall frames with bracings such as X, V and Z bracing. The main difference from our study is that the frames were planar.

The technique allows members grouping and selects the required steel sections for beams, columns and bracing members from a set of standard steel sections. The frame used for the optimization procedure is three-bay, 15-storey frame. It is shown that Xbracing system with pinned beam-column connections produces lightest frame.

In Pavlovic, Krajnc, & Beg (2004) cost function analysis in the structural optimization of steel frames is presented. It is outlined that generally the fabrication and erection costs of the structures are disregarded. The minimum weight does not always mean the most economical solution in the structural design. Therefore, they developed a cost function for the steel frames and this includes all essential fabrication and erection activities. It considers both manufacturing costs as well as material costs. It is formulated in an open manner, offering users to define their own parameters on the basis of a certain production line.

Optimization of Steel Frames:

In structural design process, there are lots of parameters affecting the design. These are; past experience, tests, research, engineer's capability etc. So for a specific building there is not a single design. Every engineer can design the building in a different way. The designer makes the initial design, analyzes the building and decides if the building is safe or not. If it is safe enough, he/she can search for a way to design the structure in a more economical way. So the design process is somewhat a trial and error process and every step takes considerable time. The need for the computer software and optimization techniques arises from this aspect.

Evolutionary Algorithms:

Evolutionary algorithms (EAs) are search methods that are inspired from natural selection and survival of the fittest of the nature. EAs are different from more traditional optimization techniques because they search the design space using a population of solutions, not a single point. At every iteration of an EA, the poor solutions are eliminated. The solutions having high fitness values are recombined with other solutions that have high fitness by interchanging their parts. These solutions are also mutated by making some changes to their elements. To generate new solutions recombination and mutation are used, and it is hoped that these new solutions move towards regions where the good solutions lie.

EP was developed by Fogel first. Intelligent behavior was viewed as the ability to predict the next state of the machine environment. When an input symbol is presented to the machine, the machine generates an output symbol, which is compared to the next input symbol. The current output symbol represents a prediction of the next input symbol. The quality of the prediction is measured by using a payoff function (Dumitrescu, Lazzerini, Jain, & Dumitrescu, 2000).

III. PROPOSED METHODOLOGY

3.1 OPTIMUM DESIGN OF STEEL FRAMES USING EVOLUTION STRATEGIES

3.1.1 Optimization

Optimization can be described as the process of having the best solution of a given objective(s) while satisfying certain restrictions. It can also be defined as finding the minima or maxima of a given objective function under some constraints. Being a very widely used phenomenon in today's world, optimization is used to improve business processes in practically all industries such as operations research, artificial intelligence, computer science, and structural design. There are mainly four elements of optimization.

These are:

- Design variables
- Constraints
- Objective function
- Design space

In order to improve a property of a structure, one has to change some parameters of it. These parameters are called design variables. Design variables can be a cross-sectional dimension or simply be a cross-section type from a given set of steel sections. Design variables can take either discrete or continuous values. For instance in case of having a set of steel sections that we can purchase from, we need to use discrete design variables. If we want the variable to assume

any value between some boundaries, then we use continuous design variables. Some design variables can also be set to some specific values that are not to be changed during the design process. These parameters are called preassigned parameters.

Constraints are some special conditions that the design must satisfy in order to be accepted as a feasible design. This can be the cross-sectional dimensions of a column to be in a range or a stress in a member not to exceed a given value. There are two different constraint types. These are geometric constraints and behavior constraints. The need for a geometric constraint may arise from fabrication limitations or aesthetics. A typical example for a behavior constraint is the strength of a member.

Objective functions are the functions that measure the quality of the design. Different solutions are compared according to their objective functions. For structural optimization, minimization of cost, weight, displacement, stress or load can be used as objective function. If the problem has a single objective function, it said to be a single-criterion optimization problem. If it has multiple objective functions, it is a multi-criteria optimization problem.

There are mainly three types of structural optimization. These are size optimization, shape (geometry) optimization and topology optimization.

Size optimization deals with changing the dimensions of a given element. Typical example for a size optimization can be seen in Figure 3.1.

Shape optimization deals with changing the shape of the element, such that optimum locations of nodes in a finite element model of the structure are determined.

In topology optimization, the best distribution of material for a given structure is found. An optimal structure is generated by carving out material from a given space, for a given amount of material. Figure 3.2 is an example for a topology optimization.

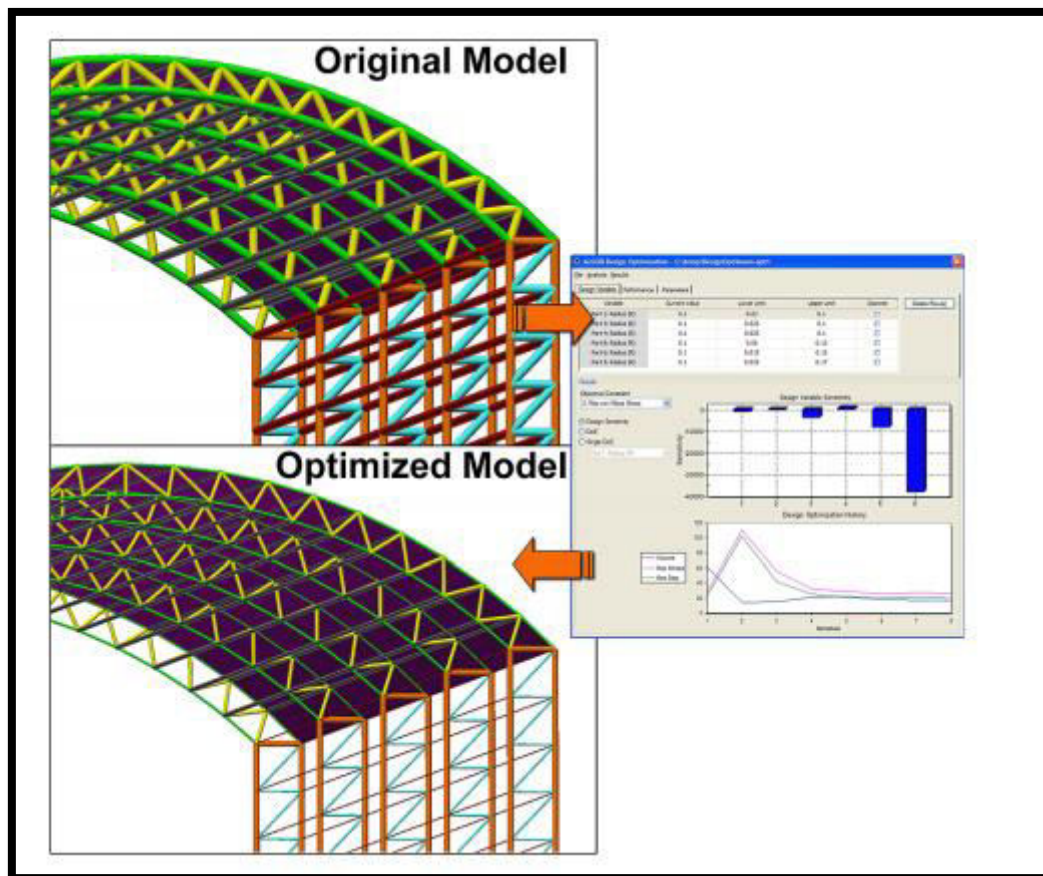


Figure 3.1 Size Optimization (Algor, 2009)

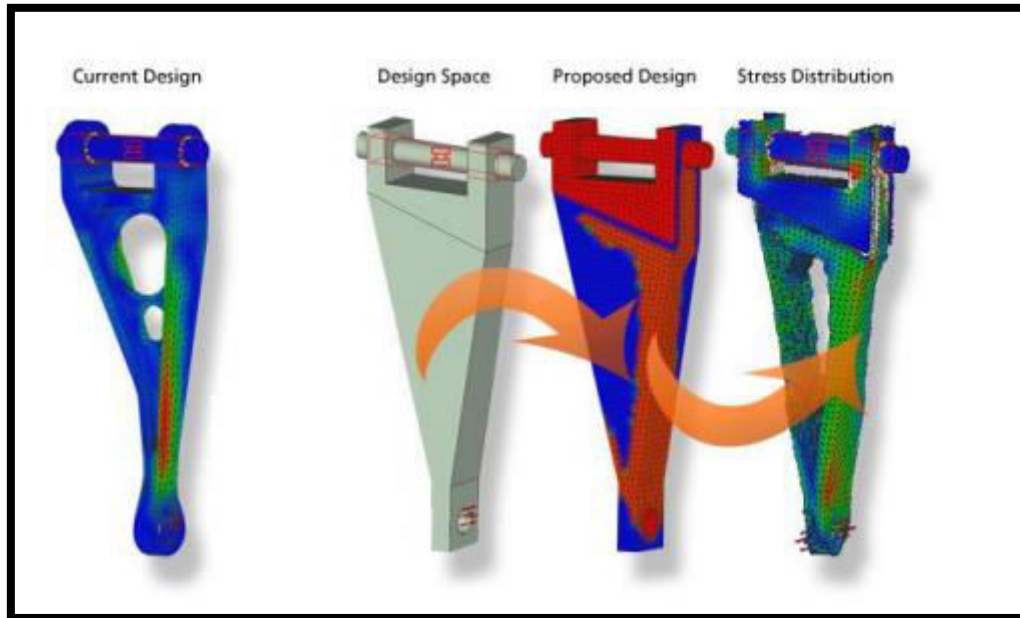


Figure 3.2 Topology Optimization Example (Topologica Solutions, 2009)

3.2 Evolution Strategies

The fundamentals of ESs were originally laid in the pioneering studies of Rechenberg (1965, 1973) and Schwefel (1965) at the Technical University of Berlin. They developed the first (simplest) variant of ESs, which implements on the basis of two designs; a parent and an offspring individual. Today, the modern variants of ESs are accepted as $(\mu + \lambda)$ and (μ, λ) (Schwefel, 1977, 1981). Both variants employ design populations consisting of μ parent and λ offspring individuals, and are intended to carry out a self-adaptive search in continuous design spaces. The extensions of these variants to solve discrete optimization problems were put forward in the following three studies in the literature: Cai and Thierauf (1993), Bäck and Schütz (1995), and Rudolph (1994). Amongst them, the one proposed by Cai and Thierauf (1993) refers to a non-adaptive reformulation of the technique and has probably found the most applications in discrete structural optimization. The approach proposed by Bäck and Schütz (1995) corresponds to an adaptive reformulation of the technique, which incorporates a selfadaptive strategy parameter called mutation probability. Another adaptive reformulation of ESs is presented by Rudolph (1994) for general non-linear mathematical optimization problems.

3.2.1 Optimization Routine

As in all EA techniques, the underlying idea of ESs rests on simulation of natural evolution in an effort to evolve a population of individuals (designs) towards the optimum. In this framework, both continuous and discrete adaptive ESs make use of a common optimization routine featuring a generation-based iteration of the technique. This routine is outlined in the flowchart shown in Fig.

Concerning this flowchart, the first two steps consist of setting the generation counter μ to 0 and creating an initial population $\mu(0)$. The initial population consists of μ parent individuals, which are customarily created through a random initialization. Hence, it is highly likely that the initial population consists of a high number of unfit individuals that violate the constraints or highly overestimate the optimum. The next step is to evaluate the individuals' performances, where each individual is assigned a fitness score according to how well it satisfies the objective function and constraints of the problem at hand. In the following step, an offspring population $\mu'(\mu)$ is created through a sequential application of recombination and mutation operators to the parent population. The offspring population consists of λ individuals, which also undergo an evaluation process (step 5 in Figure 2.4) to attain a fitness scores. Next, in step 6, the survivors of parent and offspring populations are determined via the selection operator, which identifies the only difference between $(\mu + \lambda)$ and (μ, λ) variants of ESs. In the $(\mu + \lambda)$ variant, the operator is

implemented by choosing deterministically the best μ individuals from a sum of $(\mu + \lambda)$ (parent and offspring individuals). On the other hand, the (μ, λ) excludes the parent population from the selection mechanism – instead the best μ individuals are chosen only from the λ offspring individuals. This completes one generation in the optimization procedure, accompanied by an increase of the generation counter by one (step 7). The surviving individuals in generation t make up the parent population $P(t+1)$ of the next generation. The loop between steps 4 and 8 is iterated in the same way for each new value of the generation counter until a termination criterion is satisfied.

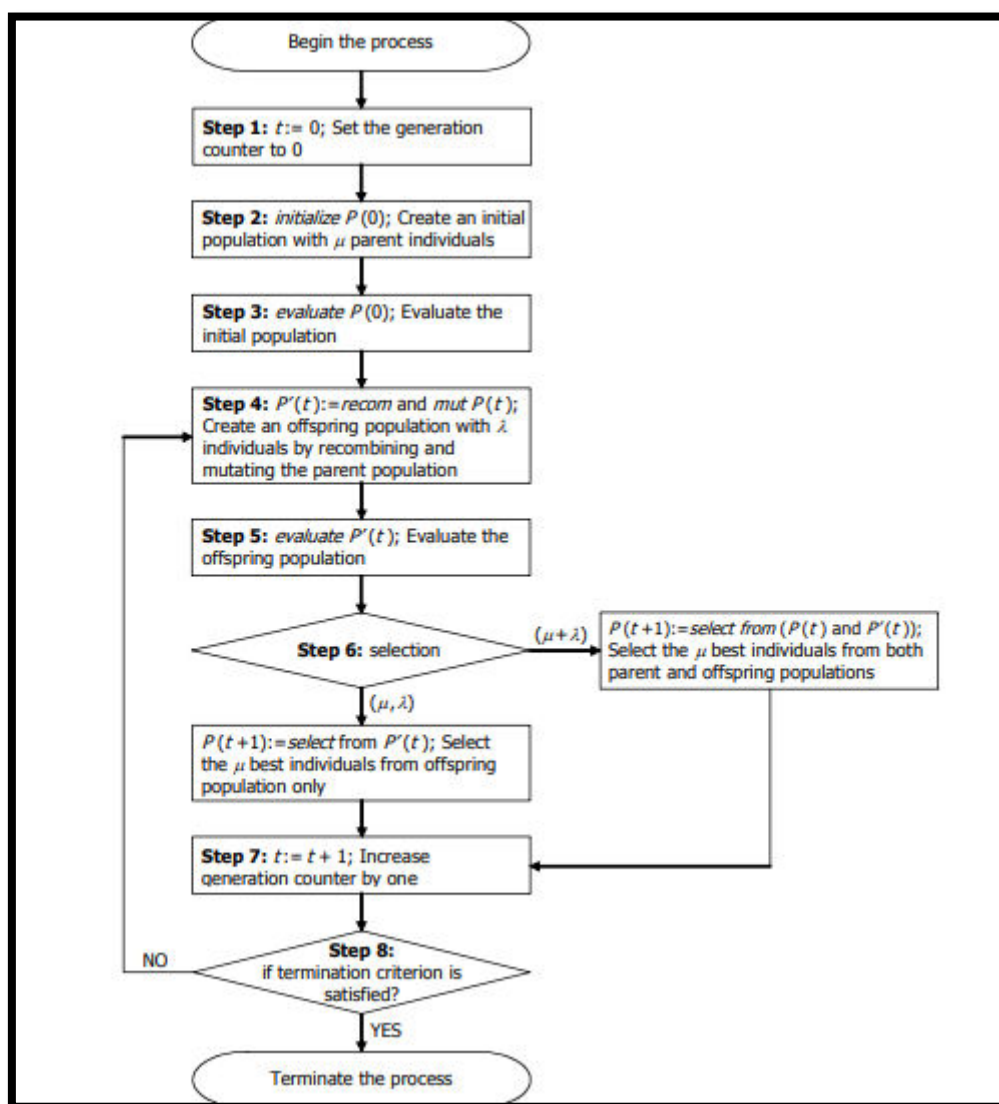


Figure 3.3 Optimization Routine

3.3 Calculation of Wind Loads According to ASCE 7-05 Method 2

ASCE is the abbreviation for the American Society of Civil Engineers and the standard is for calculating the Minimum Design Loads for Buildings and Other Structures.

In ASCE 7-05 there are three different methods for calculating the wind loads for structures.

Method 1 is named as “Simplified Procedure” and in order to use this method the building must meet 7 specific requirements. Some of them are:

- It must be a simple diaphragm building as defined in section 6.2 of ASCE 7-05.
- It must have roof slopes less than 10 degree.
- The mean roof height of it must be less than or equal to 30 ft.

Method 2 is the “Analytical Procedure”. This method will be explained in more detail in the following section since it is used throughout this study. This method is applicable to structures of all size.

Method 3 is the “Wind Tunnel Procedure” and it is not an analytical model as the name implies and it is mainly used for irregular shaped buildings.

3.4 BRACING SYSTEMS

A steel frame can be strengthened in various types to resist lateral forces. These systems are, moment-resisting beam-column connections (model-A) , braced frames with moment-resisting connections (model-B to model-G) , braced frames with pin-jointed connections (model-H to model-J) and braced frames with both pin-jointed and moment-resisting connections (model-K to model-M). An engineer can select one of the lateral load resisting systems. In steel buildings the most widely used method of constructing lateral load resisting system is using braced frames. Hence, the main concern is to select the appropriate bracing model and to decide the suitable connection type.

Bracing systems are used in structures in order to resist lateral forces. Diagonal structural members are inserted into the rectangular areas so that triangulation is formed. These systems help the structure to reduce the bending of columns and beams and the stiffness of the system is increased.

Simple braced non-sway frames may be considered as cantilevered vertical trusses resisting lateral loads primarily through the axial stiffness of columns and braces. The columns act as the cords in resisting the overturning moment, with tension in the windward column and the compression in the leeward column. The diagonals work as the web members resisting the horizontal shear in axial compression or tension, depending on the direction of inclination. The beams act axially, when the system is a fully triangulated truss. They undergo bending only when the braces are eccentrically connected to them. Because the lateral loads are reversible, braces are subjected to both compression and tension; they are most often designed for the more stringent case of compression (Taranath, Wind and Earthquake Resistant Buildings, 2005).

The building, which is braced, displace very little under horizontal forces so that the horizontal displacement of them may be neglected and the building may be classified as non-sway building. Braced-bays are located such that they have minimum impact on the structural layout, but taking into account the manner in which the frame is to be erected, the distribution of horizontal forces and the location of any movement joints in the structure. Braced-bay systems comprise diagonal, cross, 'K' and eccentric bracing arrangements. The advantage of triangulated systems is that the bracing elements are subjected only to tension or tension and compression in the absence of bending moments. Consequently, the members are relatively light providing a very stiff overall structural response. In the case of eccentric bracing, the system relies, in part, on flexure of the horizontal beam elements. This particular arrangement provides a more flexible overall response which is most effective under seismic loading conditions. Where a single diagonal (as opposed to 'cross') brace is used, it must be capable of resisting both tensile and compressive axial forces to allow for the alternating direction of wind load. Under these conditions, it is recommended that the bracing member has a minimum slenderness ratio of 250 to prevent the self-weight deflection of the brace limiting its compressive resistance. Although many different section shapes can be used as compression braces, a circular hollow section is the most efficient structurally. It should be noted that, in addition, hollow sections offer a greater resistance to corrosion and can be more aesthetically pleasing than open sections.

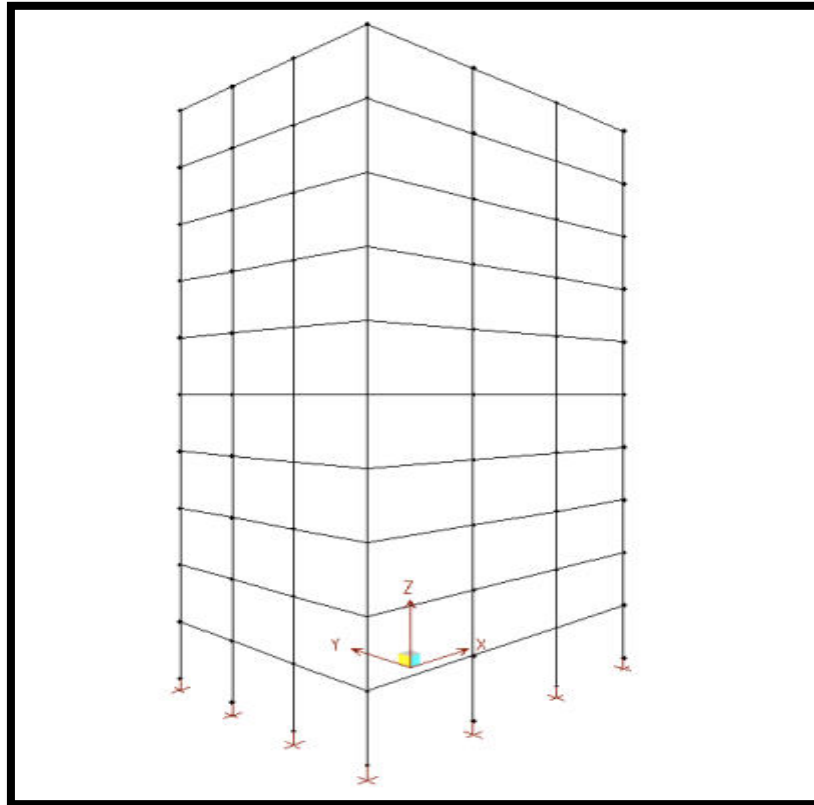


Figure 4.1 Model-A (No-Bracing)

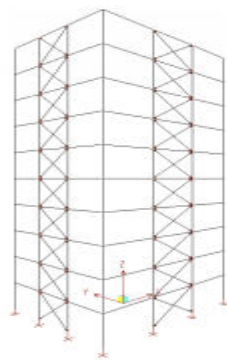


Figure 4.2 Model-B

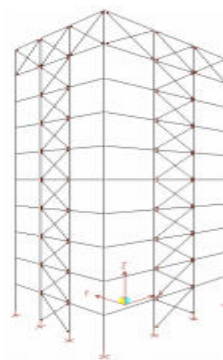


Figure 4.3 Model-C

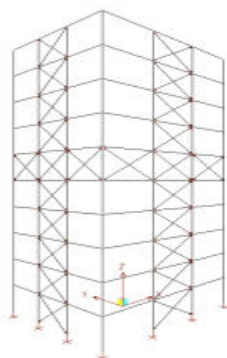


Figure 4.4 Model-D

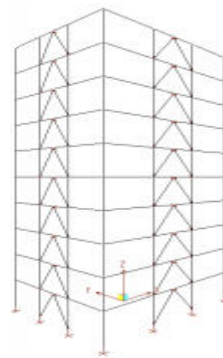


Figure 4.5 Model-E

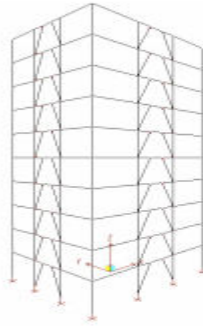


Figure 4.6 Model-F

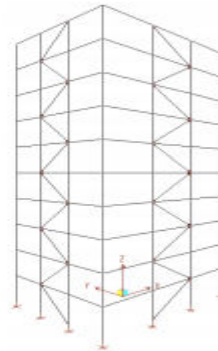


Figure 4.7 Model-G

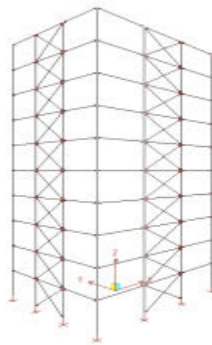


Figure 4.8 Model-H

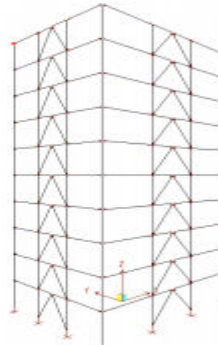


Figure 4.9 Model-I

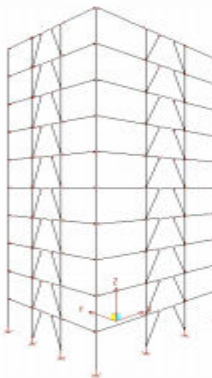


Figure 4.10 Model-J

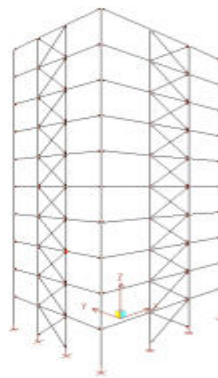


Figure 4.11 Model-K

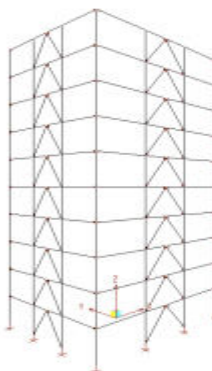


Figure 4.12 Model-L

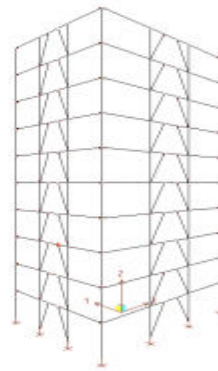


Figure 4.13 Model-M

- Model A: No bracing, all column and beam connections are rigid.
- Model B: Middle span is supported by X-type framework and all beam and column connections are rigid.
- Model C: Middle span is supported by X-type framework and all beam and column connections are rigid. Moreover top floor is supported by Xtype framework.
- Model D: Middle span is supported by X-type framework and all beam and column connections are rigid. Moreover middle floor is supported by X-type framework. - Model E: Middle span is supported by K-type framework and all beam and column connections are rigid.
- Model F: Middle span is supported by Knee-type framework and all beam and column connections are rigid.
- Model G: Middle span is supported by Z-type framework and all beam and column connections are rigid.
- Model H: Middle span is supported by X-type framework and all beam and column connections are pin-jointed.
- Model I: Middle span is supported by K-type framework and all beam and column connections are pin-jointed. - Model J: Middle span is supported by Knee-type framework and all beam and column connections are pin-jointed.
- Model K: Middle span is supported by X-type framework and only outer most beam-column connections are joints.
- Model L: Middle span is supported by K-type framework and only outer most beam-column connections are pin-jointed.
- Model M: Middle span is supported by Knee-type framework and only outer most beam-column connections are pin-jointed.

IV. CONCLUSION

Since the design of structures is a challenging task, not all the designers can manage to make a perfect or optimum design. This yields to non-economical structures since the sections that are used are larger than they supposed to be. Since economy is one of the most important considerations of the design process, designers should find a way of making more economical designs. This is possible only if he/she uses some optimization techniques.

The main starting point of the ESs is to solve problems that have real-valued parameter. After some time, ESs were developed to solve problems that has discrete parameters. For a structural design problem, there is definite number of members and there is generally a steel set of sections that the designer chooses from. This is a typical example of a problem having discrete parameters.

The aim of this study is to determine the optimal configuration of lateral bracing models in steel structures subjected to wind forces. For this purpose three different structures (10, 20 and 30 floored) are prepared and optimum designs of them with twelve different bracing models are carried out. The wind speed is assumed to be 125 mph and as a lateral load, only wind load is taken into consideration. In case of having other types of loads like earthquake loads, the performances of the models might change slightly.

General conclusions of the results are as below:

- Bracing always decreases the weight
- For low-rise structures, there is no need to use rigid connections
- For low-rise structures, the bracing choice is not very important
- There is no need for an outrigger truss in low-rise models
- Z-type bracings are more applicable to low-rise structures
- Model having a high weight may lead to a low-cost model. Typical example to this case is L-20
- Pin-jointed structures are always heavier than the rigid jointed ones
- Importance of the rigid connections increases with the structure height
- Knee-type bracing does not give good results. We only consider of using this type of bracing when there is space limitation

V. FUTURE SCOPE

- By using bracings in the structures, the displacement of the structure greatly reduced can be changed or altered. Hence the further study can be done by examining the behavior of the storey building due to wind load forces and Time history analysis.
- We can also study on the behavior of Bending Moment, shear Force etc.
- We can study other types of bracings in different Zones for the different soil type conditions.
- We can study for the different sections in steel structures and compare with and without bracings.

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