Optimal Design of Lattice Wind Turbine Towers

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SUMMARY:
Depleting organic-based energy sources and climate change are two of the grand challenges that the human kind has to solve in the 21st century. These concerns have led to widespread implementation of renewable energy sources around the world. Wind power obtained from wind turbines is one of the renewable energy sources, which grows at a rate of 30% annually. This global interest in wind energy brought a huge competition among manufacturers and therefore it is critical to obtain the optimized designs for every component of the wind turbines towers. This paper investigates the cost savings that could be achieved in design of steel wind turbine towers through optimization. Only lattice towers are considered in the study because higher cost savings can be achieved with these towers when compared to tubular counterparts although the latter is considered more aesthetically pleasing and maintenance friendly, especially in cold climates. The novelty of this work is due to following: (1) in addition to material cost, the cost of foundation and connections is taken into consideration; (2) all the details of a rigorous structural analysis are included in the finite element models; and (3) realistic loading conditions including both the wind and earthquake loads are applied on the towers. The study outlines a procedure to turbine manufacturers in their selection process for wind energy field implementations.

Keywords: Wind turbines, structural optimization, lattice towers, seismic and wind load design

1. INTRODUCTION

In the recent years due to the worldwide interest on renewable energy resources, there has been significant advancement in wind energy technology. The capacity of the turbines has increased from 100kW in 1980s to as high as 7 MW today. The increased capacity of the wind turbines also led to the increase in the height of the supporting towers since more energy can be extracted at higher elevations. In a typical wind turbine project, the cost of the tower constitutes about 20-30% of the total cost of the project. Therefore, selection and optimization of the tower structural system is still very important to develop a structurally and economically reliable wind turbine field.

Two types of structural systems: lattice and tubular, are often used for wind turbines. Each system has pros and cons. Tubular systems are formed by rolling steel plates and joining them by flanged bolted connections. Due to their aesthetically pleasing look and predictable dynamic and fatigue properties, they are more commonly preferred in the industry. However, as the height of the tower increases, the thickness of the tubular sections becomes very large and this results in an increase in the manufacturing cost. In addition, it becomes more challenging to transport and mount these heavy steel sections in the field. On the other hand, lattice systems are formed by connecting L-shaped steel profiles through bolting. The truss action and larger base dimensions of this system help resist the applied loads more effectively leading to a lighter structural design. In addition, the wind loads are reduced due to the lattice topology. Considering the use of standard profiles and bolted connections, the manufacturing cost is less than tubular sections. Since the lattice tower can be transported to the field in multiple small pieces, they also offer savings in terms of construction costs. Despite, their vulnerability against fatigue loading, less aesthetically pleasing look, and maintenance issues in cold regions, as the tower heights and rotor dimension gets larger, it is expected that the lattice systems will still be used for wind turbines applications.

In parallel with increasing availability of computational power in the last decades, the studies on optimization of structural systems have drastically increased. One of the first studies on optimization of planar steel trusses is by Goldberg and Samtani (1987). Today, there is a vast literature on optimization of steel trusses. It is beyond the scope of this article to discuss previous work in detail; however, it is important to note that in a significant number of these studies steel trusses were used only as example structures for developing and testing the efficiency of optimization algorithms (e.g. Huang and Arora, 1997; Manoharan and Shanmuganathan, 1999; Erbatur et al., 2000; Lee and Geem, 2004). Design optimization of lattice trusses used as power transmission (e.g. Kocer and Arora, 2002; Taniwaki and Ohkubo, 2004; Umesha et al., 2005; Shea and Smith, 2006; Guo and Li, 2011), communication (e.g. Jasim and Galeb, 2002) or wind turbine towers (e.g. Long and Moe, 2012) has been investigated in literature. Although the structural configuration, members and the design process are very similar, the load conditions vary significantly depending on the use. The majority of studies for lattice wind turbine towers did not include the seismic loads in design optimization because these structures are generally located in non-seismic regions. However, with the increasing popularity of wind-turbines in the United States, an increasing number of these structures are being placed in the Western United States due to higher wind energy, however, this region is also prone to high seismicity. Amongst several of the studies cited above, those by Taniwaki and Ohkubo (2004) and Kocer and Arora (2002) are amongst the very few to consider seismic loading in design optimization of lattice towers for power transmission. The former study utilized the optimal synthesis method for shape, material and design optimization of a 218 bar transmission tower for shape, material, and size. The objective function included not only the cost of the material but also the cost of the land occupied by the structure. It was assumed that all members of the transmission tower are of circular steel pipes. The latter study on the other hand, proposed two new optimization methods that can employ continuous and discrete algorithms simultaneously. A 110 kV 316 bar transmission tower was studied to perform size optimization under both static and dynamic loads. The size optimization was carried out among equal or unequal leg steel profiles. The objective function considered only the weight of the material.

In this study design optimization of lattice steel towers for wind turbines is performed. All the main contributors of cost (i.e. members, connections and foundation) are considered. A discrete optimization algorithm; namely, taboo search, is utilized to perform size optimization. The structural members are selected from equal leg angles available in the market. The innovative aspects of the optimization method in this study are the consideration of all relevant cost items and load combinations for both wind and earthquake. In the following, first, the selected wind turbine tower is described along with the design procedures. Next, the finite element model, optimization problem and algorithm are discussed. The results are presented and the paper is concluded with a discussion on future research directions.

2. SELECTION AND DESIGN OF THE WIND TURBINE TOWERS

A 100 kW small wind turbine, shown in **Figure 2.1**, available in the market is selected to conduct this study. The height of the tower is determined as 24 m. The loads acting on the tower due to the turbine is calculated based on IEC 61400-2 (2006) and shown in **Figure 2.1(Left)**. The wind load acting on the tower is assumed to be 59 m/s. Exposure category C and topographic category I is assumed considering that the turbine would be installed in an open terrain with no abrupt changes in topography. Since the tower is an energy structure, the importance factor is taken as II. **Figure 2.2** illustrates the wind pressure distribution along the height of the tower. The maximum wind pressure is calculated as 1.423 kPa. No ice loading is applied to the tower. It is assumed that the wind tower is located in Palm Springs Wind Farm with geographical coordinates 33° 54' 24.80" N, 116° 33' 24.07" W. The seismic design spectrum is calculated and the earthquake forces are obtained according to the lateral force procedure of ASCE 7-10 (ASCE, 2010). The combinations of gravity, wind and earthquake forces shown in **Table 2.1** are considered.

Table 2.1. Load combinations considered in analysis.

Combination No.	Gravity Load Factor	Wind Load Factor	Earthquake Load Factor
1	1.2	1.6	0.0
2	0.9	1.6	0.0
3	1.2	0.0	1.0
4	1.2	1.0	0.0
5	0.9	0.0	1.0

The initial design and analysis of the tower is performed using the computer software PLS-TOWER (Power Line Systems, 2012). 3-D truss elements are used in finite element modeling and geometric nonlinearity is included. The design checks are performed based on TIA-222-G (2005) specification, that is, the axial load values from finite element analysis are compared to the axial load capacity per TIA-222-G. In TIA-222-G, the equations to calculate axial load capacity are provided based on the slenderness limits according to the placement of structural members in the tower and according to the number of bolts. While selecting the structural members, the slenderness ratio is kept below 150 for leg members, 200 for braces, 250 for redundant members.

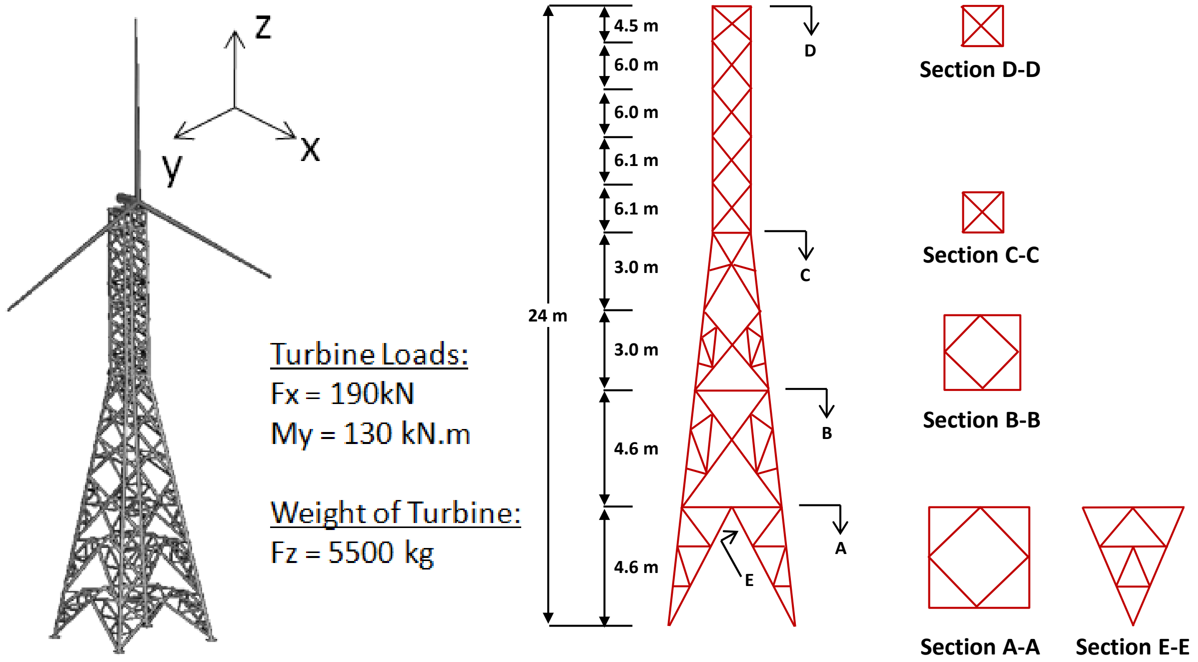

Figure 2.1. (Left) wind loads acting on the tower, (Right) outline drawings of the tower

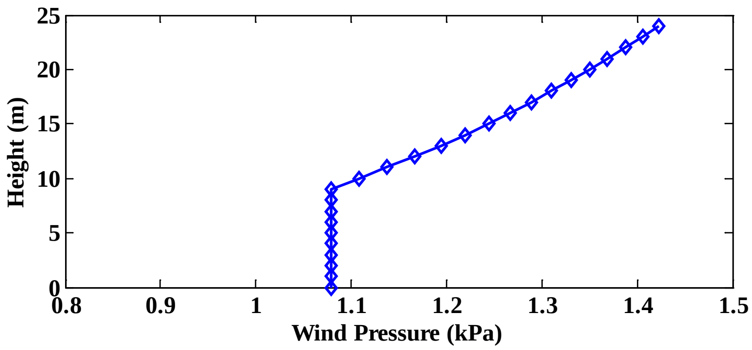

Figure 2.2. Wind pressure acting on the tower as a function of height

3. MODELING AND OPTIMIZATION

3.1. Finite Element Models

Structural analysis during optimization is performed using a different finite element analysis program; namely, ZEUS NL (Elnashai et al., 2010). A finite element model of the lattice tower in ZEUS NL is provided in **Figure 3.1**. Fiber-based beam-column elements are used to model the structural elements and proper releases of the constraints are introduced to represent the pin connections. Two types of analysis are performed: Eigenvalue, and material elastic, geometrically nonlinear static. The periods and mode-shapes are only used to understand the effect of optimization of section sizes on the dynamic characteristics of the tower, as presented in **Section 4**. The first three mode shapes are shown in **Figure 3.1.** As expected, the first two modes are bending of the tower in two orthogonal directions while the third mode is torsion. Material elastic, geometrically nonlinear analysis is used to obtain the element forces during optimization and perform the design checks according to TIA-222-G as mentioned above. Since geometric nonlinearity is accounted for in structural analysis, it is not possible to superimpose the element forces from gravity, wind and earthquake loads, i.e. a separate analysis has to be run for each load combination. To reduce the computational demand, only the first three of the load combinations that are listed in **Table 2.1** are used to perform the design checks.

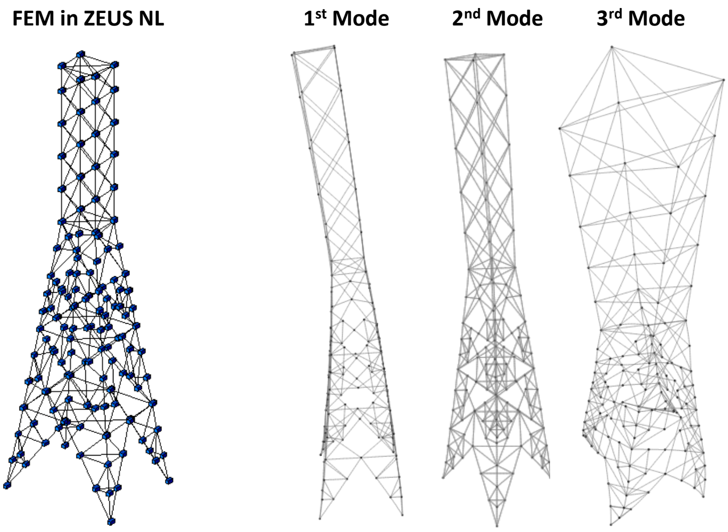

Figure 3.1. Finite element model (FEM) in ZEUS NL (Elnashai et al., 2010), and first three mode shapes

Taking into account the constructability issues, the elements are divided into eight groups based on their location and functionally, and each group is assigned a specific section during optimization. **Table 3.1** provides the details of element groups. All the elements are assigned a specific L-shaped steel profile. The density, yield strength, modulus of elasticity, shear modulus and Poisson ratio of structural steel used in finite element models are provided in **Table 3.2.**

Table 3.1. Groups and locations of the structural elements [refer to **Figure 2.1(Right)**]

Group No.	Location
1	Braces in lower part of the tower (e.g. section E-E)
2	Middle elements of section B-B, elements of section C-C and D-D, elements of section E-E
3	Braces at top, 1st level
4	Braces at top, 2nd to 5th level
5	Frame in third level from bottom (i.e. 5.2 m to 11.2 m)
6	Main frame at top third level
7	Main frame from base up to the top third level
8	Frame in second level from bottom (4.6 m to 5.2 m)

Table 3.2. Steel properties

Density	7800 kg/m^3
Young modulus of elasticity	200 GPa
Shear Modulus	77000 MPa
Poisson Ratio	0.3

3.2. Optimization Problem and Algorithm

The objective function for the optimization problem in this study is the total cost of wind turbine tower including the cost of structural steel members, connections and foundation. The total cost, *C*, is given by

$$C = \sum_{i=1}^{N_m} m\rho A_i L_i + \sum_{i=1}^{N_b} b_i + 4hdtf \quad (3.1)$$

where m is the cost of steel (\$/ton), ρ is the unit weight of steel (ton/m^2), A_i and L_i are the cross-sectional area and length of ith member, N_m is the total number of elements, b_i is the material and installation cost per bolt (\$), N_b is the total number of bolts, h, d and t are the width (m), length (m), thickness (m) of the footings, and f is the cost of material (reinforcing steel and concrete) for the footings (\$/m^3). It is known that the cost of materials (structural and reinforcing steel, and concrete) and labor (connections) are dependent on the geographical location and time. Therefore, to reduce this dependency, the costs of connections and foundation are converted to an equivalent steel weight.

The decision variables of the optimization problem are selected as the cross-sections of the elements in each of the groups indicated in **Table 3.1**. As mentioned earlier, equal leg sections are selected for each group from a list of 120 sections available in the market. The section sizes vary from 20x20x3 mm to 250x250x28 mm. The feasibility of each design is determined through the design checks as described earlier. The design checks can also be considered as the constraints of the optimization problem. The footings are designed based on the maximum reaction force at any of the four supports and the cost is calculated according to Eqn. (3.1).

In this study, taboo search (TS) algorithm is used to obtain to minimize the total cost of wind turbine towers. TS algorithm is due to Glover (1989, 1990), and it is generally used to solve combinatorial optimization problems as in this study where discrete steel sections constitute the decision variables. TS employs a neighborhood search procedure to sequentially move from a combination of design variables $\boldsymbol{x}$ (e.g. section sizes) that has a unique solution $\boldsymbol{y}$ (e.g. total cost), to another in the neighborhood of $\boldsymbol{y}$ until some termination criterion has been reached. To explore the search space, at each iteration TS selects a set of neighboring combinations of decision variables using some optimal solution as a seed point. Usually a portion of the neighboring points is selected randomly to prevent the algorithm being trapped at a local minimum. TS algorithm uses a number of memory structures to keep track of the previous evaluation of objective functions and constraints. The most important memory structure is called the taboo list, which temporarily or permanently stores the combinations that are visited in the past. TS excludes the solutions in the taboo list from the set of neighboring points that are determined at each iteration because in most cases the evaluation of objective functions and/or constraints are computationally costly. A flowchart of the algorithm is provided in **Figure 3.2**. An advantage of the TS algorithm is that it naturally lends itself to parallel processing, which is often needed to solve problems where evaluating the objective functions or the constraints is computationally costly. For instance in this study, the evaluation of constraints (design checks) requires performing a structural analysis of the tower for each load combination, which is a daunting task when thousands of such analysis are necessary.

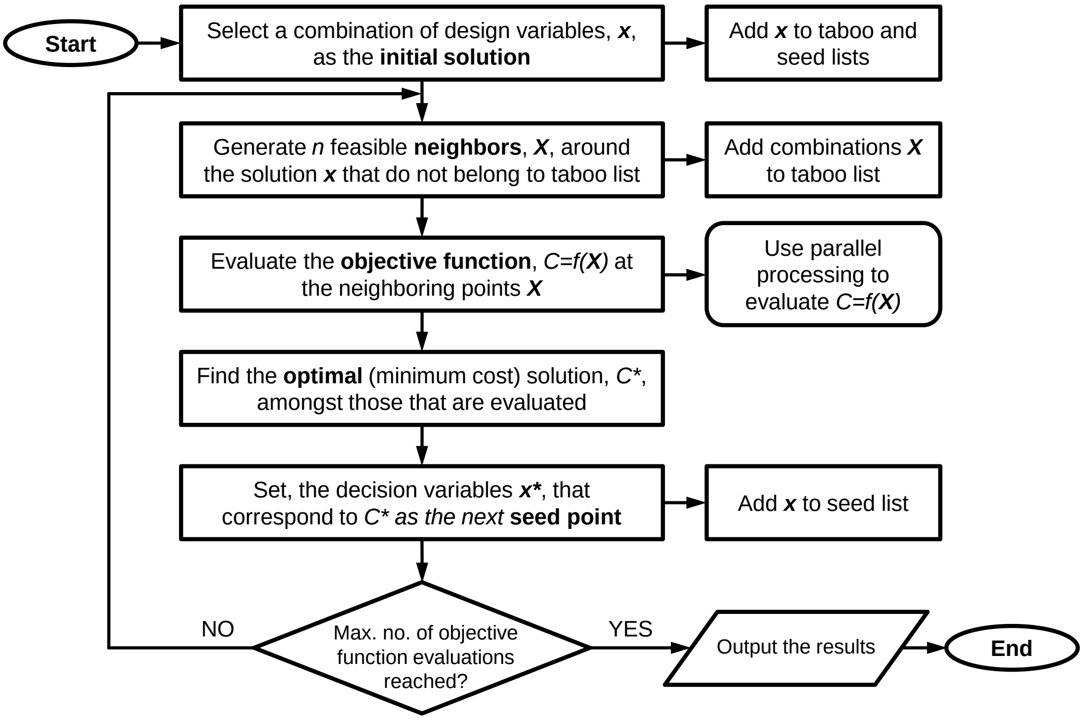

Figure 3.2. The flowchart of the taboo search algorithm

4. RESULTS AND DISCUSSION

The progression of total weight during optimization is shown in **Figure 4.1**. The initial total weight (in terms of equivalent steel weight) of the tower before optimization is approximately 111.5 kN. It is observed that this value reduces to 86.3 kN after approximately 900 evaluations of the objective function using TS algorithm. This amounts to approximately 22.5% decrease in the total weight.

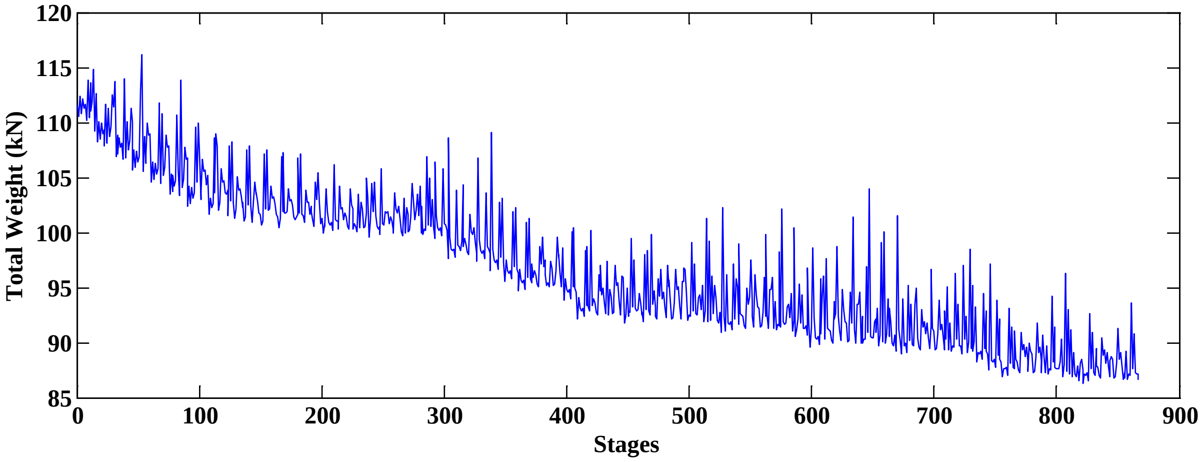

Figure 4.1. The flowchart of the taboo search algorithm

Six solutions from the optimization process are identified and tabulated in **Table 4.2.** The combinations of the section for each solution are shown in the first column where each number corresponds to a specific equal leg section whose properties are provided in **Table 4.1.** For instance section number nine has equal legs with 35 mm long and the thickness of each leg is 3 mm. It is observed from the results in **Table 4.2** that the tower and hence the connection weight reduce, while the footing weight remains the same during optimization. The latter is mainly because the self-weight of tower does not change significantly when compared to total weight of the turbine. The first three modes of vibration are also given in **Table 4.2**. It is seen that the first and second mode periods increase from 0.36 sec to 0.4 sec while the third mode increase from 0.039 sec to 0.044 sec. These increases in the modal periods are considered to be minimal to alter the dynamic characteristics of the tower as long as the structure remains in the elastic range.

Table 4.1. Equal leg sections in the identified solutions

No.	Section	No.	Section	No.	Section
9	35*35*3	52	90*90*6	82	140*140*15
13	40*40*3	58	90*90*13	83	150*150*12
14	40*40*4	60	100*100*10	84	150*150*14
23	50*50*6	64	100*100*14	85	150*150*15
24	50*50*7	65	100*100*16	87	150*150*18
46	75*75*7	67	120*120*15	91	160*160*19
48	75*75*10	78	130*130*16	92	180*180*15

Table 4.2. Progression of optimal solutions

Sections numbers for each group	Tower weight (kN)	Connection weight (kN)	Footing Weight (kN)	Total Weight (kN)	1st and 2nd Mode (sec)	3rd Mode (sec)
14,24,48,60,67,83,87,92	63.841	12.768	34.863	111.472	0.363	0.039
13,23,48,58,64,82,87,91	55.500	11.100	34.863	101.463	0.395	0.042
13,23,46,58,64,78,85,84	52.128	10.426	34.863	97.417	0.402	0.044
9,23,46,58,64,78,85,77	46.714	9.343	34.863	90.920	0.403	0.044
9,23,46,58,52,78,85,65	43.900	8.780	34.863	87.543	0.403	0.044
9,23,46,58,52,78,85,58	42.885	8.577	34.863	86.325	0.403	0.044

For design of lattice structures with asymmetric shapes, there exists few commercial software to conduct optimization studies. Therefore, in the current practice, the structures are often optimized by a trial and error approach and usually due to time constraints; it may not be possible to obtain the lightest design. The results in this study show that the taboo search is a promising approach that can be used in structural design offices. Despite the fact that there may be cases where the design from the optimization study cannot be used directly due to the amount design constraints, it still serves as a powerful tool to evaluate its closeness of the final to the theoretical optimum design. Therefore, it gives confidence to the engineers on the quality of the design work.

5. FUTURE RESEARCH DIRECTIONS

Loads acting on the tower have a significant impact on the optimal design because they directly determine the feasibility of solutions. It is a challenging task to determine the critical load combinations when both wind and earthquake effects are considered. In addition to selection of proper magnitudes for each load type, one has to also consider the direction of loading for a 3-D structure. In this study only three load combinations out of five that are suggested by existing codes are considered to reduce the computational demand. However, in future studies, the issue of loads has to be addressed more rigorously including the directivity effects. Additionally, in order to guide the selection of proper design, optimal solutions (for both tubular and lattice towers) have to be identified and compared for different tower heights, turbine loads, seismicity levels, and soil conditions. Other optimization algorithms also need to be tested with respect to their performance for lattice structures with asymmetric shapes. The scope of optimization parameters can be expanded to include the topology of the tower structure. A study in these directions is underway by the same authors.

REFERENCES

ANSI/TIA 222-G (2005). *Structural Standard for Antenna Supporting Structures and Antennas*, American National Standards Institute (ANSI), Arlington, Virginia, USA.

ASCE (2010). *Minimum Design Loads for Buildings and Other Structures*, American Society of Civil Engineers, ASCE 7-10, Reston, Virginia.

Elnashai, A. S., Papanikolaou, V. K. and Lee, D. (2010). *ZEUS NL - A System for Inelastic Analysis of Structures*, User's Manual, Mid-America Earthquake (MAE) Center, Department of Civil and Environmental Engineeering, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA.

Erbatur, F., Hasançebi, O., Tütüncü, İ. and Kılıç, H. (2000). "Optimal design of planar and space structures with genetic algorithms," Computers and Structures, 75(2), 209-224.

Glover, F. (1989). "Tabu Search - Part I," ORSA Journal on Computing, 1(3), 190-206.

Glover, F. (1990). "Tabu Search - Part II," ORSA Journal on Computing, 2(1), 4-32.

Goldberg, D. E. and Samtani, M. P. (1987). "Engineering Optimization via Genetic Algorithm." *Ninth Conference on Electronic Computation*, ed Will, K. M., New York, NY, USA.

Guo, H. and Li, Z. (2011). "Structural Topology Optimization of High-Voltage Transmission Tower with Discrete Variables," Structural and Multidisciplinary Optimization, 43(6), 851-861.

Huang, M. W. and Arora, J. S. (1997). "Optimal Design of Steel Structures Using Standard Sections," Structural and Multidisciplinary Optimization, 14(1), 24-35.

IEC (2006). *Design Requirements for Small Wind Turbines*, International Electrotechnical Commission (IEC), IEC 61400-2, Geneva, Switzerland.

Jasim, N. A. and Galeb, A. C. (2002). "Optimum Design of Square Free-Standing Communication Towers," Journal of Constructional Steel Research, 58(3), 413-425.

Kocer, F. Y. and Arora, J. S. (2002). "Optimal Design of Latticed Towers Subjected to Earthquake Loading," Journal of Structural Engineering, 128(2), 197-204.

Lee, K. S. and Geem, Z. W. (2004). "A New Structural Optimization Method Based on the Harmony Search Algorithm," Computers and Structures, 82(9–10), 781-798.

Long, H. and Moe, G. (2012). "Preliminary Design of Bottom-Fixed Lattice Offshore Wind Turbine Towers in the Fatigue Limit State by the Frequency Domain Method," Journal of Offshore Mechanics and Arctic Engineering, 134(3), 1-10.

Manoharan, S. and Shanmuganathan, S. (1999). "A Comparison of Search Mechanisms for Structural Optimization," Computers & Structures, 73(1-5), 363-372.

Power Line Systems (2012). "PLS-TOWER," Madison, Wisconsin, USA.

Shea, K. and Smith, I. F. C. (2006). "Improving Full-Scale Transmission Tower Design through Topology and Shape Optimization," Journal of Structural Engineering, 132(5), 781-790.

Taniwaki, K. and Ohkubo, S. (2004). "Optimal Synthesis Method for Transmission Tower Truss Structures Subjected to Static and Seismic Loads," Structural and Multidisciplinary Optimization, 26(6), 441-454.

Umesha, P. K., Venuraju, M. T., Hartmann, D. and Leimbach, K. R. (2005). "Optimal Design of Truss Structures Using Parallel Computing," Structural and Multidisciplinary Optimization, 29(4), 285-297.