Detailed comparison study among 3 cell tower alternatives (triangular, square lattice towers and monopole) preliminarily based on specific case requirements

Abstract

The cell tower alternatives have been investigated for 36 m tower height requirements by applying the general practical and theoretical points of view considerations during the comparison among the alternatives (Monopole and the Self–supporting lattice towers), where the preliminary design process has been applied for the investigation of the structural and tower service behavior to compare between the lattice towers (Square and Triangular lattice tower) based on the Euro code requirements and regulations, where only the wind action has been considered to discover which alternative will be as the best solution that deserves to be selected and going to undertake further detailed design level later for specific case of study requirements need to be reached. The selected best solution alternative will be designed in details to be constructed in a rural zone near Budapest city (Hungary). The present specific case requirements have been settled where the basic control aspects specified to control the proper alternative selection were the Aesthetical, Economical and Statical aspect. The SLS limitation specified to be not more than 0.5 degrees as a rotation effect at the tower top. Based on the obtained results and from a practical point of view after a detailed comparison among the alternatives led to set 2 valuations: the first valuation has been held between the Monopole and the Lattice towers in general (Monopole Vs Lattice towers) showed that the advantage was to the Lattice towers based, the 2nd valuation has been held between the lattice towers exclusively (Square Vs Triangular) led to select the Triangular lattice tower as the highest score gainer during the detailed comparison study presented in this paper where the applied members' cross–section has been considered beside the tower shape based.

Keywords: angle members, cell tower, CHS members, comparison study, lattice, monopole, telecommunication

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Introduction

Free–standing (lattice) and the monopole Towers are integral components for wireless networks that require height to reach the intended coverage area.[1,2] The three structural options which considered in the present case are two self–supporting towers (Triangular & Square based), and a monopole tower. Each has its own features and benefits and choosing the best option for a given site is important. If the net present value of future lease payments is greater than the total cost of erecting a tower then a tower is the best choice.[1] If an existing tower is not located at a point that optimizes your network, then you may want to consider a new structure or leasing a rooftop. Each tower is different due to its geographic location and wind–loading capabilities.[3] In order to take the decision for which is the most proper solution that will be selected for the present case to be optimized and designed in details to take place where the most 3 important criteria have been chosen to magnify the decision are the Aesthetical (Architectural, Ecological, and resemblance), Statical (Efficiency, Technical value, and the functional requirements), and Economical (Cost, installation time and maintenance cost) considerations.

Monopole vs. lattice tower comparison

Here are some general guidelines [3] for deciding which tower type has the advantage to be selected based on the presented case in this paper where the specified aspects are the Aesthetical, Economical and Statical. Based on each alternative specification would be easier to make a decision concerning the best choice which meets the requirements.

Self–supporting lattice Tower

1. Can be used for installations from 6 to 60 m.

2. Smaller installation footprint than a guyed tower, but larger than a self–supporting guyed and monopole towers.

3. Often ships knocked down, reducing freight expenses but requiring on–site assembly, Figure 1.

4. Significant wind–loading capacity.

5. The Lightweight Self–Supporting Tower is Ideal for requirements under 30 m with minimal wind–loading capacity and some options use a minimal installation footprint with simple concrete foundation.

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6. Can accommodate heavy loading of antennas and microwave dishes.

7. Less cost than Monopole.

8. The capacity of latticed tower members and connections can be described by relatively simple formulae.

9. Modeling and design are relatively easy.

10. Monopoles are generally costing higher than lattice angle towers due to higher cost of plates where Monopole requires specialized plate bending machine with high capital cost, Figure 2.

11. Ecological: The lattice structure is highly transparent so that it has a lesser effect on the landscape. Optimum ecological balance thanks to the galvanized steel structure and small concrete foundations (savings in terms of raw materials; both tower and foundations can be recycled), Figure 3.

Figure 1 (A) Lattice tower easy transport and (B) on-site assembly.

Figure 2 Less cost of angle lattice towers compared to monopole plates.

Monopole

1. Smallest footprint of all tower types.

2. Can be used for installations from 9 to 45 m.

3. Generally considered the most aesthetically pleasing structure, Figure 4.

4. In some jurisdictions, zoning permits are not required for installations under 18 m.

5. Significant wind–loading capacity.

6. Requires crane for installation.

7. Higher freight costs because a full flatbed is required for delivery.

8. The least expensive but more expensive than lattice towers.

9. Antennas are usually mounted on a monopole with a vertical separation of 3 m to 4.5 m increments.

10. High quality connection: Reliability and high quality of signal reception provides rigidity and resistance to external influences, especially in difficult icing and wind conditions.

11. Compact: The base support size allows the support of a small area of building, which is particularly important in the construction in the city.

12. Aesthetics: Exterior construction favorably differs from traditional designs, which is an important factor in the placement of towers in the city, on the territory of enterprises, protected areas, etc.

13. Operation: Placement of the equipment, cables, feeders, maintenance of stairs inside the support eliminates unauthorized access to equipment, provides weather protection, i.e., increase the service life, it allows you to carry out work in difficult climatic conditions and the result of drastically reducing operating costs.

14. Flexibility in design.

Figure 3 Lattice Tower transparent.

Figure 4 Beauty of monopole tower.

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First stage of valuation

Firstly, according to the general comparison between the free standing "Lattice" and the Monopole towers where based on the detailed elements above and according to the specified decision criteria (Aesthetical, Economical and Statical Considerations) it's possible to indicate the most proper alternative that relevant to the present design situation. Where it's obvious that the Monopole can be a good competitive especially from the Aesthetical side but from the other specifications related to the cost (Economical) and statical limit the Lattice tower was mostly the winner, therefore the Lattice tower will be chosen to be considered. In the next stage of valuation need to decide which one of the investigated lattice towers (Square or Triangular based) should be taken as a final solution and according to that another comparison study between the Square and the Triangular lattice tower will be held to achieve the goal of a significant decision.

Latticed towers preliminary investigations

In order to investigate the structural behaviour of the alternatives discussed above (Square and Triangular latticed towers) the preliminary calculations of the main bearing elements have been applied by manual calculations according to Euro code requirements and specifications.[3–8] where only a simple cantilever, Figure Figure 5A and 2D model been used during the manual based calculations, while 3D models would be used later for the detailed design by the Axis Vm 13 software application (not interesting for the present stage), see Figure 5B & Figure 5C. Worth to mention that only the wind actions have been considered during the investigations of the present case of the study presented in this paper and the tower antennas approximated to be 20 square meters projected area at the tower top (at elevation 33m to 36m), in addition the tower linear ancillaries have been considered too (Ladders and antenna cables). The tube pipes circular hollow cross sections (CHS) and equal angle (L) cross sections would be used mainly for the investigated alternatives.

a) Simple b) 2D and 3D model of Triangular Tower c) 2D and 3D model of Square Tower
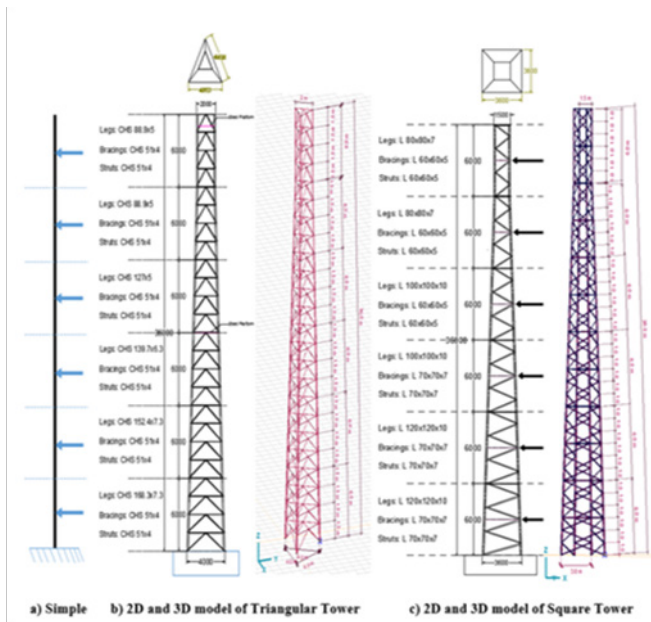
Figure 5 alternatives models.

Wind action

For the purposes of the wind force calculations; the structure should be divided into a series of sections,[3,4] where the section comprises several identical or nearly identical panels. Projections of bracing members in faces parallel to the wind direction, in–plan and hip bracing, should be omitted in the determination of the projected area of the structure. The structure should be generally divided into a sufficient number of sections to enable the wind loading to be adequately modeled for the global analysis. The wind force acting on a section or component should be determined according to 5.3 (2) of EN 1991–1–4.[9]

The wind force should be calculated by the following expressions:

– The mean wind load in the direction of the wind on the tower should be taken as (1):

$$F_{m,w}(z) = \frac{q_p}{1 + 7I_v(z_e)} \sum C_f A_{ref} \qquad 1$$

– The equivalent gust wind load in the direction of the wind on the tower should be determined as (2):

$$F_{T,W,z} = F_{m,w}(z)\left[1 + 0.2\left(\frac{Z_m}{h}\right)^2 \cdot \frac{\left[1 + 7I_v(Z_e)C_sC_d - 1\right]}{C_0(Z_m)}\right] \qquad 2$$

Design values of Wind forces according to the Annex A of EN 1993–3–1,[10] related to the reliability differentiation and partial factors for actions for masts and towers. In the present case the reliability has been chosen as class 2 and the partial factors for wind action would be ($\gamma_Q = 1.4$). The tower main internal forces (Moment and shear) have been calculated based on a simple cantilever model, where the design values of wind force have been considered acting at the middle of each section, see Table 1 & Table 2 and Figure 6 & Figure 7.
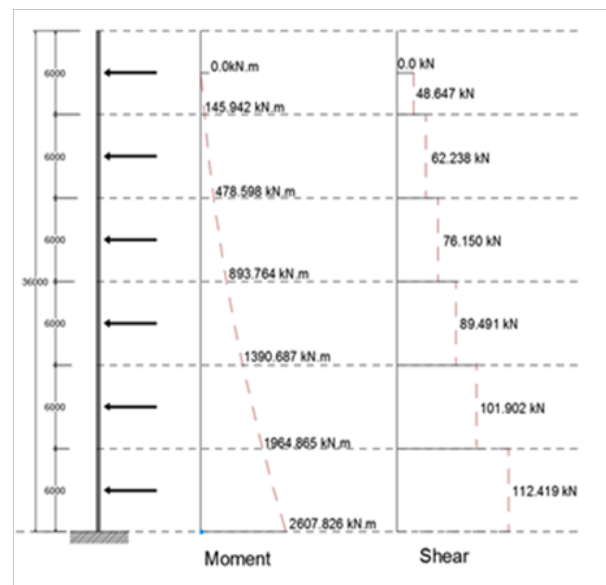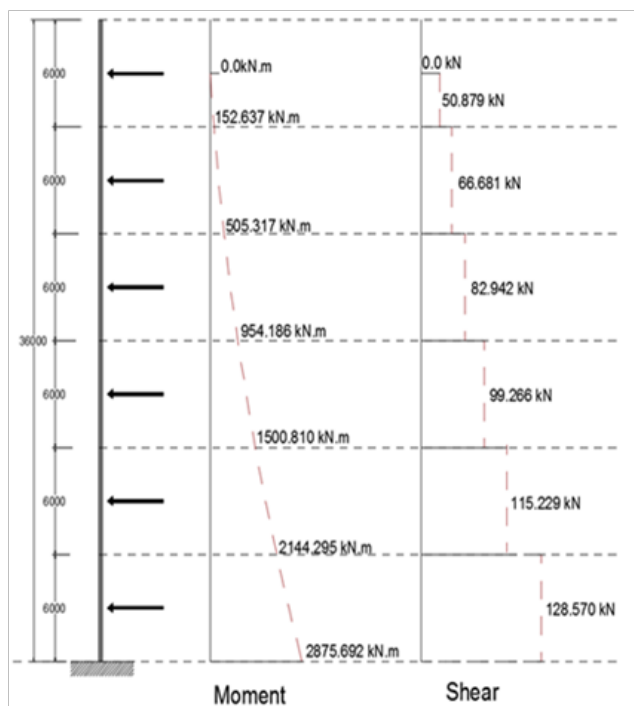

Figure 6 Triangular tower moment and shear diagram.

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Table 1 Triangular tower wind forces and internal forces

Section	Force eev. "Z" (m)	Characteristic wind force "$F_{k,i}$" (kN)	Design wind force "$F_{d,i}$" (kN)	Moment "M_i" (kN.m)	Shear force "V_i" (kN)
1	3	7.512	10.517	2607.826	112.419
2	9	8.865	12.411	1964.865	101.902
3	15	9.529	13.341	1390.687	89.491
4	21	9.937	13.912	893.764	76.15
5	27	9.708	13.591	478.598	62.238
6	33	34.748	48.647	145.942	48.647
				0	0

Table 2 Square tower wind forces and internal forces

Section	Force elev. "Z" (m)	Characteristic wind force "$F_{k,i}$" (kN)	Design wind force "$F_{d,i}$" (kN)	Moment "M_i" (kN.m)	Shear force "V_i" (kN)
1	3	9.529	13.341	2875.692	128.57
2	9	11.402	15.963	2144.295	115.229
3	15	11.66	16.324	1500.81	99.266
4	21	11.615	16.261	954.186	82.942
5	27	11.287	15.802	505.317	66.681
6	33	36.342	50.879	152.637	50.879
				0	0

Figure 7 Square tower moment and shear diagram.

Alternatives results verifications

The internal forces of the structural elements have been calculated by applying the section method at each 6m height of the tower and only the max. Critical internal forces have been considered and verified under compression and buckling,[8] (see Table 4) & (Table 5)).

The verification process has been done according to the

a. EN 1993–1–1:[10] Design of steel structures Part 1–1: General rules and rules for buildings; 5.5 Classification of cross sections; 6.2.4 Compression resistance

b. EN 1993–3–1:[11] Euro code 3 – Design of steel structures– Part 3–1: Towers, masts and chimneys – Towers and masts;

Where the tower has been verified for rotation as SLS, compression & buckling as ULS. All the members were class 1 during cross–sections classifications, therefore plastic cross section check required. Need to mention that the applied steel grade in case of CHS members which used in the triangular lattice tower was for the legs 275 MPa and the bracings as 235 MPa, while the steel grade in case of angle members which used in the Square lattice tower was for the tower legs 355 MPa and the bracings as 235 MPa see Table 3.

Table 3 Applied steel grade

Tower type	members	Members C.S	fy (MPa)
Triangular lattice tower	Legs	CHS	275
	Bracings		235
Square lattice tower	Legs	L	355
	Bracings		235

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Table 4 Triangular tower buckling verification (ULS)

Section	Members	i (mm)	λ1	Lcr,1 (m)	λ‾ eff	Φ	χ	NEd (kN)	Nb, Rd, Pl (kN)	Utilization (%)
1	Leg	57	86.82	1.5	0.303	0.557	0.977	752.815	991.79	75.9
	Diagonal	16.7	93.91	2.5	1.514	1.785	0.366	27.88	50.862	55
	Strut			1.95	0.59	0.715	0.894	22.304	124.017	18
2	Leg	51.4	86.82	1.5	0.336	0.571	0.969	630.231	886.642	71.1
3	Leg	47.2			0.366	0.584	0.962	501.821	698.124	71.9
4	Leg	43.2			0.4	0.601	0.953	368.582	502.126	73.4
5	Leg	29.7			0.582	0.709	0.897	230.266	325.012	70.8
6	Leg	29.7			0.582	0.709	0.897	84.259	325.012	25.9

Table 5 Square tower buckling verification (ULS)

Section	Members	i (mm)	λ1	Lcr,1 (m)	Lcr,2 (m)	λ‾ eff	Φ	χ	NEd (kN)	Nb, Rd, Pl (kN)	Utilization (%)
1	Leg	36.7	76.409	2	1	0.77	0.894	0.743	564.836	606.339	93.2
2	Leg								476.805		
3	Leg	30.4				0.924	1.05	0.646	384.503	432.987	88.8
4	Leg								288.337		
5	Leg	24.4				1.159	1.334	0.501	186.1	190.527	97.7
6	Leg								71.953		
1,2,3	Diagonal	21.2	93.913	3.7	–	1.881	2.555	0.233	38.126	40.863	93.3
4,5,6	Diagonal	18.2		2.34	–	1.538	1.911	0.329	30.599	35.511	86.2

Assumption

The internal force of the struts of each section have been considered equal to the design value of the horizontal component of the bracings force in case of K–bracing system applied to the triangular lattice tower, while it has so small compression force tend to zero in case of single web bracing "V–bracing" system applied to the square lattice tower therefore it has been used for the purpose of ancillaries support (Ladder & Antenna cables) and the tower platforms.
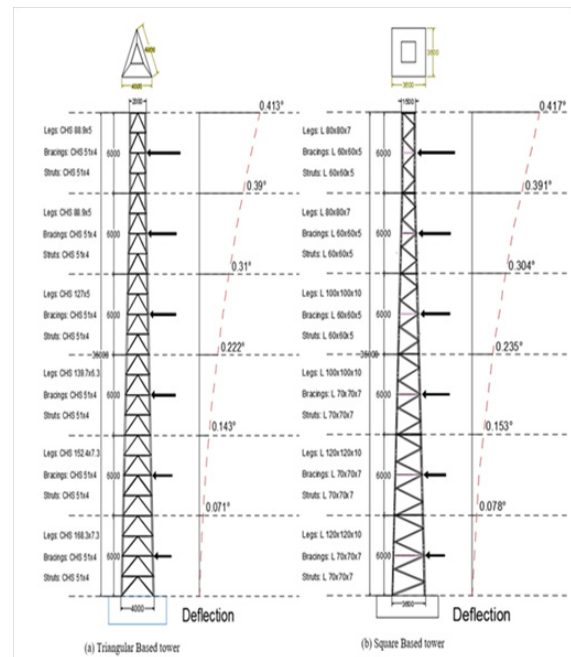
Note: Based on the criticality the Buckling Check as ULS and the top rotation of the towers as SLS were governing the design.

For the deflection calculations, the wind load has been reduced where it has been considered in the present design as 60% of the characteristic wind load with a limit of deflection 0.5° degrees at the tower top, where the individual deflection at each section with modulus of elasticity E = 210 GPa and Inertia calculations of each section (*J*) have been calculated as (3) and the cumulative deflection at the tower top have been calculated and corrected by 0.85 as (4). According to the obtained results the max rotation of the triangular tower reached 0.413 degrees, while it was 0.417 degrees for the square lattice tower see Figure 8 (Table 4) & (Table 5).

$$\Phi_i = \frac{M_{0i}}{E \cdot J_i} \qquad 3$$

Where: $M_{0i} = \left[M_i + \frac{M_{i-1} - M_i}{2} \right] \cdot Z$ (Z = 6m)

$$\Phi = \frac{\sum \Phi}{0.85} \qquad 4$$

Figure 8 Alternatives rotation results verification (SLS).

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Detailed comparison between the square and triangular based lattice towers

Some points should be clarified related to each tower concept in order to give a percentage for each solution where the tower with higher percentage will be chosen as the most proper solution to be constructed and allocate in a rural place near Budapest (Hungary). As already clarified in Figure 8 above that there were different members cross–sections have been applied for each investigated tower, where CHS members have been used in the triangular based tower Figure 9A, while an angle members have been used in the square based tower Figure 9B, therefore the comparison elements will be based on 2 criteria where the first based on the members cross–section which leading to a comparison between the CHS and angle members[12] while the second criteria will be based on the tower shape (Square and Triangular). Although other configurations of angular members exist, e.g. cruciform or boxed configuration, it will be demonstrated in this paper that the circular hollow section (CHS) members have better mechanical properties e.g. structural efficiency, weight advantage and lower wind resistance (less projected area) compared with the angle cross–sections.[12,13] The CHS members have no weak axis for overall (flexural) buckling unlike angle sections and stiffer for torsion. Worth to mention that the tube section has a more aesthetical appearance. The outer smooth and curved surface of tubes also results in better corrosion protection against weather elements seeing that there are fewer corners and cavities for moisture build–up.
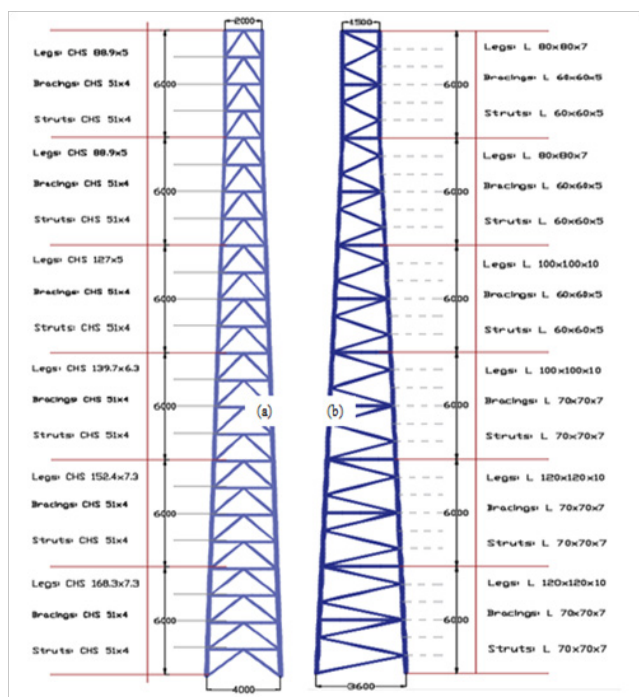

Figure 9 (A) Triangular lattice tower with CHS members; (B) Square Lattice tower with angle members.

Economics of structural hollow sections

Although structural efficiency and torsional strength are definite advantages[12,13] when it comes to design a structural member, it is important to mention the disadvantages of using circular hollow sections. Firstly, the cost per ton of hollow sections compared with hot rolled sections is higher. The reason is that the manufacturing of circular hollow sections comprises a number of stages compared with a single stage for open sections. For towers produced of angular profiles the costs of the manufacturing are rather low since normally the joints consist of bolts and plates and no welding is included. The joints for lattice sections of circular profiles are traditionally more complicated and time–consuming.

Tubular profiles and telecommunication structures

In order to establish a relevant comparison between angular profiles and tubular profiles, the following design parameters were used:

1. Wind load; and

2. Buckling capacity

For reasonable solidity ratios (effective area/ total area of tower panel), it may be seen that the drag coefficient decreases when the solidity ratio increases.[3,8,12] Wind resistance of flat–sided profiles (angle members) is frequently higher than for tubes due to the larger projected area of angle sections. Furthermore, it is shown that hot–rolled circular profiles produce higher buckling capacity compared with angular members based on non– dimensional slenderness ($\tilde{\lambda}$) due basically to the larger tubes radius of gyration (i) value than for angle sections[12] as it's shown in the equation as (5).[11]

$$\tilde{e} = \frac{L}{i \cdot \lambda_1} \qquad 5$$

Another aspect generally found with angular member towers is that more bracing members are required compared with tubular member towers owing to the buckling efficiency of CHS members. Thus, towers manufactured from angular sections require more erection preparation and cost. However, angular members pack better for the purpose of transportation; this however does not necessarily imply a lower cost. The outer smooth and curved surface of tubes also results in better corrosion protection against weather and less surface area of tubes is advantageous for surface protection (painting, coating, etc.).

Square vs. triangular based tower shape

1. Following are some points to consider when specifying towers [1, 4, and 7]. As will be seen, the square angle design has no advantage whatsoever over the triangular design, and the triangular design has many advantages over the square design. This is evidenced by the fact that the majority of the world's major tower/mast manufacturers operate in an environment where the finest quality raw materials are available and are not limited to a certain steel supply. These modern manufacturers provide triangular towers as their primary product.

2. The square tower design is old–fashioned and antiquated. Some designs date back to the 1800s and were based on the availability of material, existing design capabilities and ease of manufacture. Almost any steel fabricator can design and manufacture square angle towers or masts. Square angle towers are specified in many cases because of the long–standing designs that have not been updated over the years. These structures have been the accepted standard, since many departments and users do not have the in–house structural engineering capacity to evaluate modern designs, and take the time to update their requirements.

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3. Square tower design is very popular in developing countries where updated technology and sophisticated machinery are not available yet. It exists only because there is no other choice, and what was good enough 100 years ago, is all that is available today.

4. Towers and masts constructed from angle material have a much higher wind load than the more sophisticated triangular round member tower. A triangular round member tower is much more aerodynamic and therefore has lower wind resistance.

5. Because of the higher wind load on the structural members, more reinforcing pieces are necessary, and therefore the structure when completed has many more components and connections than a triangular tower.

6. A square tower with all of this extra material is not stronger than a triangular tower designed for a similar load.

7. As a result of the square angle design, there is more labor involved to assemble the material, more possibilities of pieces not fitting, and more connections to become loose and require maintenance.

8. Triangular towers only require 3 foundations; square towers require 4. There are considerable cost savings in civil works and concrete using a triangular design, but should be mentioned that the square based tower stiffer against deflection at the tower top more than the triangular based due to 4 legs dependent where in the preliminary design the deflection of the square tower based was 0.417 degree with high leg and bracing members utilization see Table 6, while it was 0.413 degree with leg and bracing utilization less than 80% for the triangular based tower see Table 7.

9. Less construction area required for the triangular based than the square based tower where the construction area required of the triangular tower was 6.92 m2 while it was 12.96 m2 for the square based tower approximately the double construction area required, see Figure 10.

10. The triangular based tower with CHS members was lighter than the square tower with angle members thus saving freight costs, and is constructed of fewer pieces. This is possible because of the higher strength steels that are currently available for the more high–tech tower/mast designs where the triangular tower weight was 4334.261 kg while it was 5045.356 kg for the square based tower.

11. Less painting area required for the triangular tower with CHS members than the square tower with angle members, where the painting area of the triangular tower was 123.764 m2 while it was 180.612 m^2 for the square tower.

12. With round main members (legs) equipment such as dish mounts, platforms etc. are mounted with 'U' bolts, and therefore can be moved from location to location without drilling additional holes in the structural members of the tower. Antenna mounts for example can be added to the structure without any field punching, drilling or welding.

13. There is an old–fashioned argument that pipe members corrode from the inside, and since the corrosion is hidden, it cannot be maintained or corrected. Back when pipe members were first used in construction, the material was not hot dip galvanized inside after fabrication. With today's modern fabrication procedures and galvanizing technologies, this condition does not exist. Back

to back angle members can also corrode from the inside, and cannot be maintained. The secret is in the fabrication/galvanizing procedure.
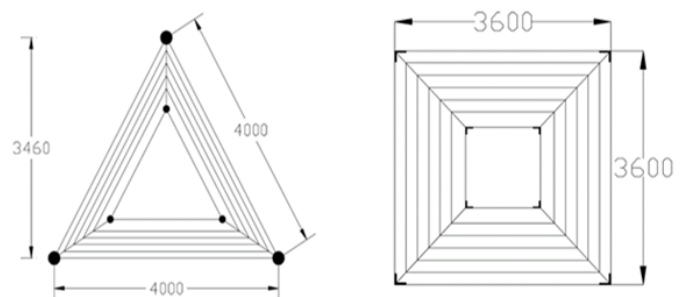
14. Due to the availability of larger sizes of higher strength round structural steel shapes, round member pipe/solid towers can be designed with single piece main structural members. Angle towers require 'back to back' bolted or welded members ("built up" sections) to provide the strength required for some of today's tremendous antenna loads and tower heights.

Table 6 Square based tower deflection and member's utilization

Square Based tower				
Deflection (˚)	Leg C.S	Utiliz. %	Bracing C.S	Utiliz. %
0.417	L120×120×10	93	70×70×7	93.3
	L100×100×10	89	60×60×5	86.2
	L80×80×7	98		

Table 7 Triangular based tower deflection and member's utilization

Triangular Based tower				
Deflection (˚)	Leg C.S	Utiliz. %	Bracing C.S	Utiliz. %
0.413	CHS 168.3×7.3	76	CHS 50×4	55
	CHS 152.4×7.3	71	CHS 50×4	
	CHS 139.7×6.3	72	CHS 50×4	
	CHS 127×5	73	CHS 50×4	
	CHS 88.9×5	71	CHS 50×4	

Figure 10 Towers construction area comparison.

Second stage of valuation (final decision)

It's obviously that the higher percentage was going to the triangular based tower according to the all available giving and the preliminary investigations results where all or most of the advantages were to the CHS members and the Triangular shape based tower therefore and according to all that guide lines the decision become much easier to make and finally the triangular based tower will be selected as the best solution and will undergoing further design and optimization process in next future paper.

Conclusion

According to the first stage of valuation where a detailed

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comparison has been held between the Lattice tower and Monopole where all the available elements were refereeing to select the lattice towers to achieve the aim of the cost "Economical" due to the specified tower height as 36 m, where the Monopole tower could be more economical alternative for the towers that higher than 50 m. and the Statical aspects have been achieved also by the lattice tower. in spite of that the aesthetical considerations were not completely in the lattice towers side because the Monopole was so a great competitive in this point and if we can approximate the comparison mark as 2:1 for the lattice tower then obviously the lattice tower will be selected in this competition basing on the specified criteria in this paper. In the second stage of the valuation where this time the comparison held between 2 types of the lattice towers based on the shape (Square and Triangular lattice towers). It was very clear according to all the advantages that the triangular tower has against the Square based that make the decision should be sloped to the most proper selection where the specified study criteria could be achieved added to that the used members cross sections in the triangular tower were have a great priority to be selected where the CHS members have a great advantages against the angle members which used in the Square tower, and according to that the Triangular based lattice tower would be selected in this competition.

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Conflict of interest

The author declares there is no conflict of interest.

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