MASTS AND TOWERS

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1. INTRODUCTION

Within the last decades the need for tall structures has accelerated with the requirements for effective communication especially the advent of radio, radar and television. Latest the exponential growth in the use of cellular phones has meant a new era for towers and masts, however smaller in height but larger in number.

There are many challenges for the engineers associated with this tall and slender structures, and many experts have stated that "a guyed mast is one of the most complicated structures an engineer may be faced with". This statement is unfortunately underlined by the fact that the number of collapses of masts is relatively far greater than for other types of structures.

In addition to the complexity in the structural system itself, the predominant loads of masts and structures are natural loads as wind and ice, loads that also effects the structural behaviour. The wind load is a dynamic load and the slender structures are sensitive to the dynamic part in the wind. Ice on a tower or mast will by its weight change the dynamic behaviour, as well as it may increase the wind drag of a lattice tower or mast dramatically.

The overall layout of telecommunication masts and towers is govern by the requirements to the transmission and receiving conditions. Added hereto the access and working conditions for installation and service are important issues for the design. The first requirements often leads to relatively tall structures or in mountainous areas a smaller structure on the top of hills or mountains. Both solutions leads to various problems with regard to analysis, design and construction.

2. BASIS OF THE DESIGN

Before starting the analysis and detailed design it is very important for the designer to establish the basic requirements for the actual structure. Here the professionalism of both the client and the designer and their co-operation is vital for the result.

Unfortunately the situation is quite often a combination of a not too experienced client hiring a designer who is not familiar with the special problems associated with design of masts and towers. Over the years this combination has created many structures that are not suitable for the intended purpose, that are too safe or more often are unsafe. The latter has in some incidences lead to failures or even a total collapse of the structure.
Sometimes compromises are necessary. A single structure is often required to carry UHF omni directional aerials, VHF radio, microwave link dishes, telephone arrays as well as various monitoring aerials, etc.

Some of the factors to be considered by the client and the designer are for instance:

- mean aerial height for each aerial system,
- directions for the various directional antennas,
- wind drag on each element of the array and dependent on wind direction,
- size, weight and disposition of all feeders and cables,
- the permitted angular rotations in azimuth and elevation of each aerial above which the broadcast signal is significantly reduced,
- the need for all-weather access to some of the aerials,
- besides the known antenna and aerial configuration the possible future extension should be defined,
- atmospheric ice formation on the structure and aerials and its likelihood to occur with high wind,
- wind drag of the structure itself without ice and with ice if feasible,
- the degree of security required,
- the available ground area and access to the site,
- the geological nature of the site,
- the overall cost of land, foundations and structure,
- the cost and implications of future maintenance or structural replacement,
- any special planning considerations imposed by statutory bodies,
- the aesthetic appearance of the structure.

The above list is far from being complete, and any one of these factors can influence, or even define, the primary choice of the optimum layout of the structure. Should the structure be a guyed mast or should it be a free-standing tower is quite often a choice to be taken.

3. ANALYSIS

The predominant load on towers and masts is the wind load, and in some areas also the atmospheric icing of the structure may have important influence on the design. Especially when icing is combined with wind this may be decisive for the design in some countries.

The wind is a dynamic load and slender structures like towers and masts are sensitive to dynamic load, they are flexible and they have low structural damping characteristics. It is therefore essential that towers and masts are analysed for the dynamic response of the structure to the wind. In the case of self-supporting towers, whose natural frequencies usually are well separated, the response of the structure to wind gusts is governed by the fundamental mode of vibration. This enables simplified analysis procedures to be adopted using appropriate gust response factors. Nevertheless, care needs always to be exercised in the design, especially for heavily eiffelated tower configurations.

When it comes to guyed masts the analyses are not simple, in contradictory. “A guyed mast is one of the most complicated structures an engineer may be faced to”, this statement has been given by many experts and unfortunately it is underlined by the fact that “The number of collapses of guyed masts is relatively far greater than for other kind of structures”.

Fig. 1: The tallest mast in the World, the 648 m high long wave mast in Konstantynow, Poland collapsed in 1991

Fig. 2: The mast shaft is a column elastically supported by non-linear guys.

Fig. 3: Atmospheric icing and in combination with wind may be decisive for the design in some locations

There are several reasons for the complexity of guyed masts. Some of them are due to the static system of a mast shaft as a column subjected to bending moments and elastically supported by non-linear guys, which stiffness besides the actions on the mast are dependent of the loading directly on the guys themselves, for instance wind and ice. Some of them are as mentioned due to the nature of the loads, namely natural loads as wind and ice, where an accurate estimation of the design values and combinations often is difficult. Most important is perhaps that the wind load acts dynamically and guyed masts are sensitive to dynamic loads. If the static system of a guyed mast is complex is this nothing compared with the dynamic system. For guyed masts it is not only the fundamental mode of vibration that govern the design, as the modes are not well separated and many modes may contribute to the response of the structure to turbulent winds.

It is not only the modes of the shaft that are interesting but in some instances the modes of the guys are important too. The frequencies of the structure are dependent on the loading on the mast due to wind, and ice if appropriate, and also dependent on the direction of the wind on the structure. If also asymmetrically deposit of ice on the mast shaft and the individual guys shall be taken into consideration the dynamic analysis of the guyed masts will be almost impossible.

There are few computer programs available for a full dynamic stochastic analysis of guyed masts and even with the latest generation of fast high capacity computers a fully dynamic analysis of a guyed masts may run for 10 to 20 hours. Therefore considerable efforts has been expended in trying to produce simplifications for the design rules for codes and standards, and recently a relatively reliable simplified procedure has been developed and adopted in new codes, latest in the very new Eurocode 3: Part 3.1 Towers and Masts (EC3:3.1). The procedure is based on simplified static patch wind models and has for a number of different existing guyed masts been compared a full dynamic analysis with reasonable agreement.

The principle of applying the patches in the EC3:3.1 model is shown in figure 4, and in figure 5 is shown the comparison of the extreme forces in the leg members of a 160 m guyed mast. Besides the new patch model as adopted in the Eurocode 3: Part 3.1 Towers and Masts, is the former IASS Patch Wind Model compared with the result of a full dynamic analysis. In figure 6 is for the same mast compared the extreme forces in the diagonals for the three analysis models. It may be seen that the Eurocode Model is quite close to the full dynamic response analysis and that the IASS Model is clearly on the safe side.

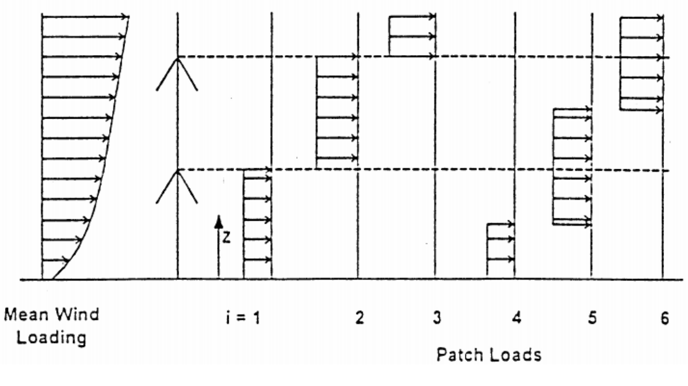

Fig. 4: Principal of applying patches on a guyed mast

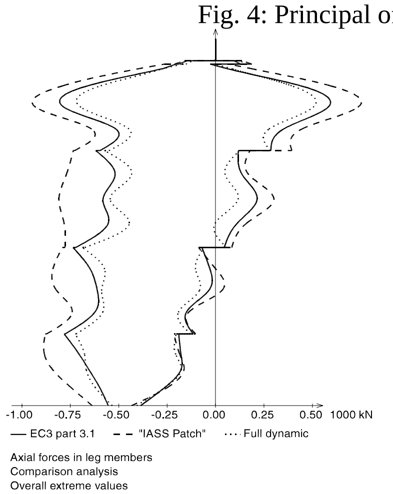

Fig. 5: Extreme forces in legs

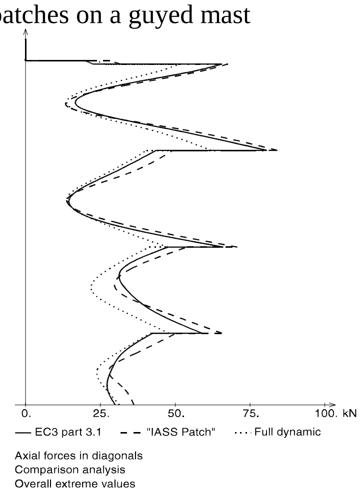

Fig. 6: Extreme forces in diagonals

4. DESIGN

The design of towers and masts is normally quite integrated with the analysis, and the optimal design often requires a series of ping-pong between what may be called design and the analysis. The first step is the choice of the overall layout of the appropriate structure, and as mentioned in chapter 2 is this choice influenced by a number of factors that in some instances even can be conflicting. Having chosen the principal layout of the structure it is necessary to undertake some preliminary designs, for instance of different cross-sections, bracing configurations, profiles for structural members, etc. as this information is necessary input for the analysis.

As the predominant loading of towers and masts is nearly always the wind load, it is important to calculate the wind resistance of the structure, including its ancillaries such as ladders and platforms, aerials and associated feeders and cables as accurately as possible. It is also important to minimise the wind resistance of the structure itself. For instance is the wind resistance of a lattice structure very much dependent on the choice of cross-section - triangular or rectangular - the bracing pattern and especially the types of profiles - circular or flat-sided -used for legs and bracing.

For example, a self-radiating medium-wave antenna mast, in which the mast itself acts as the antenna it is only the structure itself including the climbing ladder, which causes the wind resistance, as there are no antennas, cables, feeders, etc. in the mast. Using round profiles for legs and bracing the wind resistance is smaller than for flat-sided profiles, such as angle profiles, as may be seen from figure 8. A triangular cross-section of the mast instead of a square cross-section also reduce the wind resistance further, see figure 8 together with figure 7. Hence a triangular mast constructed entirely of solid round bars where also the ladder is made of solid round bars will often result in the minimum wind resistance. Unfortunately round bars are a poor profile for resisting compression forces, but despite of this such a structural outline is often an optimal solution. The relative weight of a triangular mast with solid round members and a square mast using angle sections could, for a 200m mast perhaps be 100 tons against 300 tons.

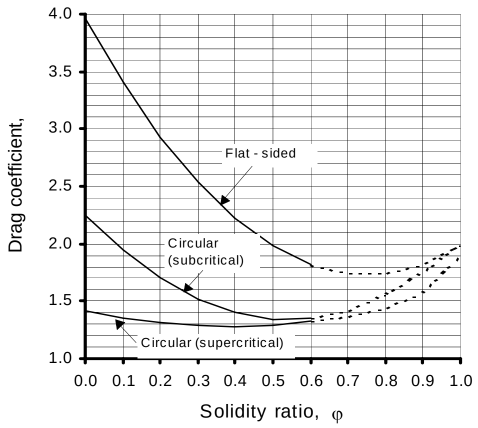

Fig. 7: Drag coefficient of square structures

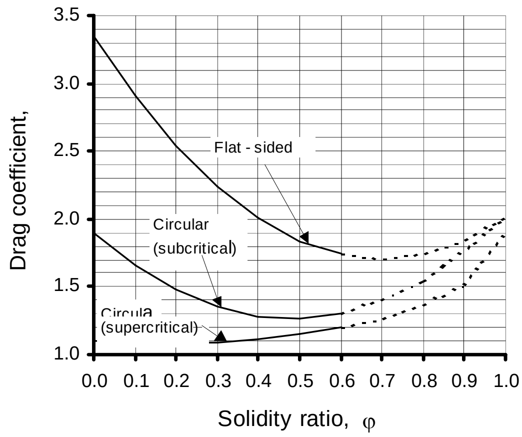

Fig. 8: Drag coefficient of triangular structures

Some antenna masts and towers are so heavily equipped with antennas, cables, feeders, etc. that the wind resistance for the structure itself is not that important even though careful considerations should be taken in the total optimisation. Also for masts and towers situated in locations where severe atmospheric icing occurs the ice may completely block the structure so the choice of both cross-section and the profiles for members is not governed by the wind resistance of the bare structure without ice.

For self-supporting towers the choice of both cross-section, triangular or square, as well as the profiles for the leg and the bracing members will also depend on more practical issues, as for instance the slenderness of the members, the practical profile sizes, their price and delivery time, the possibilities of a rational and cheap production especially of the connections, the facilities for hot dip galvanising, transportation and erection, etc. When it for the self-radiating medium-wave antenna mast may be optimal to use a all welded triangular mast in solid round bars, see figure 10, the same principle may not be feasible if it concerns a relatively high self-supporting tower, as the round bars poor stiffness will result in much too high consumption of steel.

Fig. 9: Some masts are so heavily equipped with antennas so the wind resistance of the structure itself is not so important

Fig. 10: Self-radiating medium-wave mast in solid round bars

In order to reduce the delivery costs it is not only important to reduce the costs of the raw material but also the costs of manufacturing. For towers produced of angular profiles the costs of the manufacturing are rather low since normally the joints consists of bolts and plates and no welding is included. The joints for lattice sections of circular profiles are traditionally more complicated and time consuming. As an example hereof the bolted joint between the leg and diagonals is mentioned. This has traditionally been rather complicated with gusset plates welding etc. as shown in Figure 10 from a series of standard towers to Connect-Austria. However the towers were very competitive and more than 800 of these towers were delivered within a short period.

Figure 10: Traditional joint between diagonal and legs, both circular tubes. Connect-Austria

Figure 11: New joint between diagonal and leg, both circular tubes. KPN-Orange in Belgium

As an example of a design for a series of standard antenna towers with heights from 30m to 72 m it may be mentioned that the optimum solution showed to be a triangular tower with legs and bracing in circular tubes. Tubes are very effective profiles when the design forces are compression forces as they have a large stiffness for a small steel area, and this means that the lattice structure may be quite “open” minimising the number of structural elements. The standard tower heights are shown in figure 12.

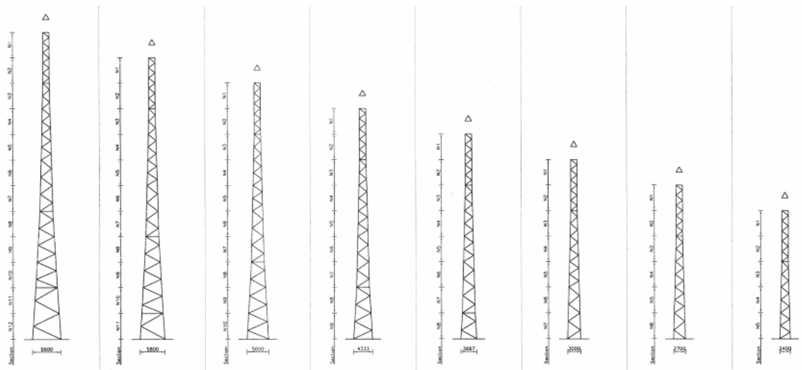

Fig.12: Series of standard antenna towers for UMTS Network in Sweden, with heights from 30 m to 72 m

On the other hand is the material price per kilo steel for tubes in general higher compared with other profiles like angles and solid round bars, as well as the connections in a tubular lattice structure normally involves welding on leg and on bracing members. For the standard series of towers a new type of simple connections was introduced so bolts could connect the diagonals without welding on the diagonals. The ends of the circular tubes are squeezed partly permitting the end to be pushed over the special designed gusset plates, as illustrated in figure 13. The gusset plate is prepared in a way that is possible to exchange the diagonals.
When using circular tubes as legs welding can not be totally avoided and involves welding of gusset plates and of the flanges for the joints of the legs, but when welding is necessary it is normally a good idea to minimise the number of elements that need welding.

Figure 13: Principles of the assembly of the diagonals

In general are guyed masts more cost effective than self-supporting towers for supporting of normal antennas the larger the required antenna height above terrain is. Is it not possible to give a precise height above which the guyed mast is optimal as this height also very much depends on other factors as for instance the cost of land for the specific location, but quite often are guyed masts used for heights more than 60 to 80 m. A kind of a hybrid solution where a guyed masts is placed on the top of a concrete tower has been adopted for main telecommunication stations where many parabolics shall be placed in moderate heights as well as the station have radio and TV antennas in high levels. The parabolics that are sensitive to rotations of the supporting structure are mounted on the rather stiff concrete tower, while the less directional sensitive antennas for radio and TV are supported by the guyed steel mast.

Fig. 14: The parabolics are fixed to the stiff concrete tower

When optimising the overall layout of guyed masts the same principles as mentioned above concerning the choice of cross-section and of profiles is valid, but many more parameters than for towers influence the optimisation of masts. In general the number of guy directions should be three, but the number of guy levels has an important influence on the design, as well the number and the placing of the guy foundations. The geometrical requirements to the antennas may to a certain degree govern the placing of the guy levels in the mast, but many other factors have influence on the design. In some countries there are a tradition for using more guy levels than in other countries and this may also be caused by the local codes and standard for the analysis and design. For instance are more guy levels used in North America, where quite simple static gust factor analysis has been codified up to very recently. Atmospheric icing may also have a direct influence on the optimum number of guys, and in areas with heavy icing it is normally a good idea to minimise the number of guys as well as the optimum guy inclination should be steeper than for masts without icing.

Another choice to be taken in the conceptional design phase is whether the mast base should be fixed to the mast foundation or it should be pinned. Even though the design of a fixed mast base is quite simple compared to a pinned masts base connection, the latter should nearly always be adopted. The fixed mast base require that the mast foundation can bear the relatively large bending moments from the mast shaft, as well as the fixed mast is very sensitive to settlement of the foundation. If the design of the mast shaft shall have any benefit of the fixed base it also require that the lowest set of guys is rather stiff. Despite of this surprisingly many guyed masts have fixed mast base, and when reanalysing of existing structures it have in many instances showed to be an effective part of a modification for overload to change the fixed base to a pinned joint.

Special Structural Design

In a guyed mast the detailing of the attachment of the guys to the mast and especially to the guy foundation is of utmost importance. It is essential that the guys can pivot as freely as possible at their attachments as any tendency to restrain the guys may result in fatigue damage. The guys will inevitably vibrate more or less due to the wind on the mast and especially due to the wind, perhaps in combination with ice, on the guys themselves. In carefully designed masts such details can be designed to achieve the highest possible freedom to pivot in all connections.

At the attachment of the guys to the guy foundations an adjustable tension system is incorporated to apply initial tension to the guys. The tension system must account for small inaccuracies in the initial guy lengths as well for future possible creep of the stranded guy ropes.

Tower and mast shaft foundations are very simple unless unusual soil conditions are encountered. However the guy foundation design is a little more sophisticated, as it needs to resist sliding, overturning and uplift. The most structurally efficient method is by attaching the guys to a vertical concrete web plate. On the front is a vertical plate fixed perpendicularly to the web plate to resist the horizontal component of the guy reactions while a horizontal concrete slab, together with the weight of the soil above, resist the vertical components of the guy reaction. Figure 16 show a sketch of a typical guy foundation.

Fig. 15: Guy attachment to foundation with tension system

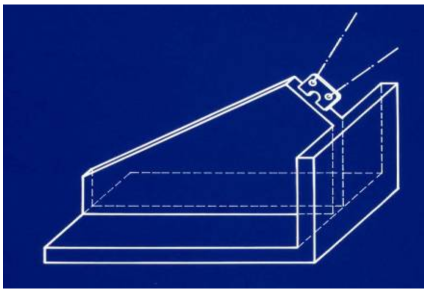

Fig. 16: Guy foundation

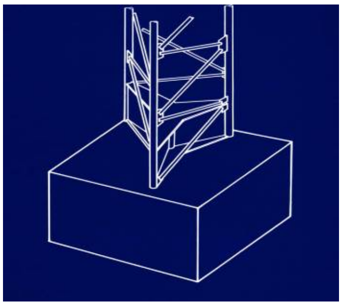

Fig 17: Mast base foundation with pinned mast bearing

5. AESTHETICS IN THE DESIGN OF MASTS AND TOWERS

Whilst the average height of new masts and towers, at least in Europe, is decreasing the rapid extension of local and commercial radio and TV channels combined with the explosion in the use of cellular telephones calls for more and more masts and towers. This considerable increase in the number of new structures has given increased importance in many countries to the aesthetic appearance of these structures, and their impact on the landscape. This has already resulted in more attention and concern from telecommunication companies towards an aesthetic approach in the layout and design of new antenna supporting structures. This is a new challenge to the designers and today a new masts or tower design often involves a close co-

operation between architects and engineers while in the past engineers/fabricators traditionally undertook the total design.
There are several examples of new designs of antenna supporting structures where the aesthetic elements pay a dominant role in the design, and in the future this will surely be a natural part of the design phase.

Fig. 18: Aesthetic tower for mobile communications (The ID-Tower which received the Danish ID-Award 1999 for outstanding industrial design)

Fig. 19: Erection of the ID-Tower

6. THE FUTURE

Even though we today have a wide knowledge of the various factors affecting the analysis, design and behaviour of masts and towers, there are still areas which are not fully understood and which need further development and research. As examples of such areas the following phenomena may be mentioned:

- assessment of atmospheric ice loading and especially the combination of wind and ice;
- galloping of guys, the true theoretical background, the computer modelling, the way to predict galloping and how to prevent/dampen when it occurs, etc.;
- non-linear dynamic response analysis of a guyed mast;
- aeroelastic instability of various mast sections/antenna configurations;
- assessment of various parameters for full dynamic response and fatigue analyses including, for instance, full-scale measurements;
- convergence on an acceptable procedure to predict vortex excitation on towers and masts supporting cylindrical sections.

Also the development of new materials, particularly those with high structural strength and good electrical resistively - may have a significant effect on mast and tower design in the future.

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