DESIGN OF GUYED MASTS

Diseño de antenas con viento

Mogens G. Nielsen and Ulrik Støttrup-Andersen
Rambøll Denmark, Bredevej 2, DK-2830 Virum, Denmark
mon@ramboll.dk, usa@ramboll.dk

Guyed masts are complex structures and challenge the design phase; the structures are tall and very slender even though they are exposed to extreme wind and occasional ice load. The numbers of failures of guyed masts are significant higher than for other structures with similar complexity and this emphasizes the statement from many experts: "a guyed mast is one of the most complicated structures an engineer can face".
Guyed masts are often used for broadcasting of radio and television or antennas for cellular phones. The masts should consequently be situated on the top of hills and mountains, where the climate often is extreme with respect to wind load and in some cases atmospheric icing. Since the wind is turbulent and the guyed masts are flexible and sensitive to dynamic load, the dynamic response becomes important in the analysis of guyed masts. The guyed masts act strongly nonlinear since the forces in the guy ropes are varying from slackened to a taut string. Over the years different methods have been used for analysing guyed masts making the methods more and more realistic: starting by a gust factor method in the American standard TIA/EIA-222, over the IASS patch wind method to the Eurocode patch wind method, which gives results close to the results from a stochastic analysis and the time domain analysis.
This paper provides a brief introduction to the analysis of guyed mast and the method for modelling the dynamic response. Furthermore different methods for modelling the dynamic response of guy rupture are discussed. Finally is an overview over the main reasons for collapses of guyed masts are presented.
Key words: Guyed masts, Dynamic analysis, Guy rupture, Design, Mast failures

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 guyed masts. There are many challenges for the engineers associated with these tall and slender structures, and many experts have stated, "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 affects 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 mast will by its weight change the dynamic behaviour, as well as it may increase the wind drag of a lattice mast dramatically. The overall layout of telecommunication masts 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 lead to various problems with regard to analysis, design and construction.

Fig. 1: The mast shaft is a column elastically supported by non-linear guys

Fig. 2: Atmospheric icing and in combination with wind may be decisive for the design in some locations

ANALYSIS OF THE MAXIMUM FORCES

The predominant load on 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 masts are sensitive to dynamic load, they are flexible and they have low structural damping characteristics. It is therefore essential that masts are analysed for the dynamic response of the structure to the wind. In the case of guyed masts the analyses are not simple, in contradictory. This is underlined by the fact that "The number of collapses of guyed masts is relatively far greater than for other kind of structures".
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. The complexity of the static system of a guyed mast is nothing compared with the complexity of 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 non-symmetrically 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. In figure 3 is illustrated some of the modes of a guyed mast compared to a tower.

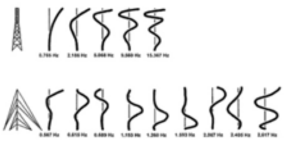

Fig. 3: Modes of a lattice tower and a guyed mast

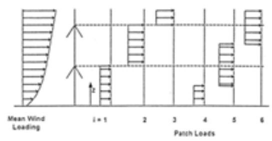

Fig. 4: Principal of applying patches on a guyed mast

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 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 Eurocode 3: Part 3.1 Towers and Masts (EC3 Part 3-1, 1997). 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 Eurocode 3 Part 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 for Towers and Masts (EC3 Part 3-1, 1997), 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. Analysis in the time domain has shown similar results as the results from the stochastic method and the Eurocode patch (Bakmar, C.B., 2004).

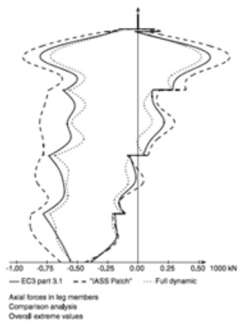

Fig. 5: Extreme forces in legs (Nielsen, M.G. 1995)

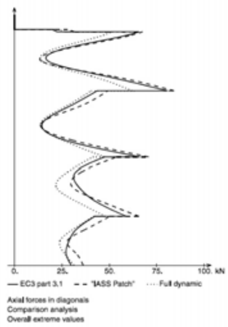

Fig. 6: Extreme forces in diagonals (Nielsen, M.G. 1995)

GUY RUPTURE

Guy rupture is a design criterion, which is seldom used when guyed masts are designed. However guy rupture relative often leads to collapses of guyed masts. The most significant incident was the fall of the tallest guyed mast in the World. Guy rupture is a critical event, which can lead to collapse of the guyed mast. Consequently it should be included in the design analysis for guyed masts in high reliability class. This is already recommended in the Eurocode for towers and masts (EC3 Part 3-1, 1997). The guyed masts must be able to withstand guy rupture in still air conditions and at a reduced wind pressure in the absence of the ruptured guy. Guy rupture is one of the most frequent reasons for collapses of guyed masts. In the following are described the three different methods in the Eurocode (EC3 Part 3-1, 1997).

The full dynamic method for guy rupture

In the full dynamic method the deflections and the forces are determined in the time domain. Consequently it is possible in the analysis to include the entire dynamic effects as well as the non-linearity's of the guys, the column effects etc. However the damping of the guys are normally neglected since the guyed masts are normally weakly damped and the time period for the analysis is very limited. The guy rupture is modelled by an instant removing of the guy force in the upper end of the ruptured guy.

Static approach for guy rupture

U. Peil has in (Peil, U., 1997) described a more conservative procedure in order to determine the dynamic actions caused by the rupture of the guy.

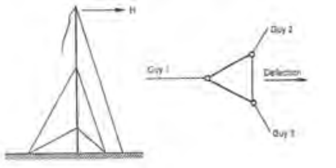

Fig. 7: The principle of the static approach for guy rupture

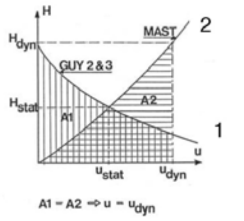

Fig. 8: Force-deflection diagram to estimate equivalent horizontal load at guy rupture

The model is developed using the assumption that the maximum dynamic amplification factor is 2 for a dynamic system forced by an impulse load. In the procedure the dynamic forces are conservatively estimated in a static calculation where the horizontal force from ruptured guy before the rupture is used as an additional action force on the system without the ruptured guy. The horizontal force should be increased by a factor 1.3 in the case of a mast with 2 stays or when a top guy is considered. The principle of the method is shown in figure 7 where H is the horizontal force that should be applied after the rupture of the guy has been removed.

Description of the simplified energy method

In the simplified energy method the guyed mast is analysed for an equivalent dynamic load resulting from the dynamic situation immediately after a rupture of one guy. This equivalent dynamic load acts in the level of the set of guys where on guy is broken and the value is estimated regarding the energy situation just after the rupture of one guy. In the simplified energy method it is assumed that the rupture of the guy takes place at the upper end of the guy, the influence of the damping and the mass distribution is neglected and the elastic energy stored in the ruptured guy before the guy rupture neglected. The simplified energy method is based upon an energy solution. Just after the rupture the two intact guys in the set loose potential energy when the mast deflects and the two guys slackens. The variation of the horizontal reaction on the mast from the two intact guys with the deflection of the guy attachment is shown on figure 8, curve 1. The deflection is positive for guys moving in the direction away from the ruptured guy and consequently the force is decreasing for increasing deflection.

The shaft and the remaining guys absorb the lost energy of the two unbroken guys. Curve 2 shows the deflection of the mast for horizontal load acting at the level of guy rupture. Consequently the force is increasing with increasing deflection. The area below curve 1 corresponds to the energy lost in the two intact guys, while the area below curve 2 is the energy absorbed in the structure. The dynamic equilibrium is obtained when the two areas are the same, corresponding to an equivalent horizontal load Hdyn and a deflection of udyn of the attachment point. Some time after the rupture the mast comes to a permanent equilibrium corresponding to the crossing point of the two curves, i.e. for a horizontal load of Hstat and a deflection of ustat. The deflection is positive for guys moving in the direction away from the ruptured guy and consequently is the force decreasing for increasing deflection.

Comparison of results with a dynamic analysis

A comparison between the three different methods shows quite good results in the two simple methods. The comparison is carried out on a guy rupture one of the upper guys in a 244 m mast, Pyhätunturi, in Finland. The full dynamic analysis was carried out in a period up to 2 seconds after the rupture of the guy and rupture is assumed to occur under still air conditions. In this period occurs the maximum bending moments of the mast shaft.

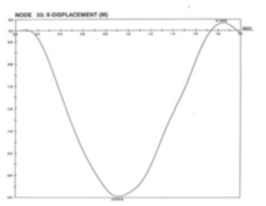

Fig. 9: Displacement of the top of the mast

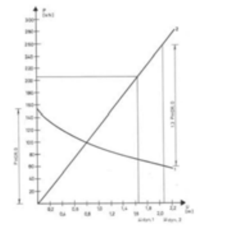

Fig. 10: Force-displacement diagram at guy level 5

The guy rupture of a guy at guy level 5 is analysed using the simplified energy model. The Forcedeflection diagram appears in figure 10. From the diagram it can be seen that the maximum dynamic deflection of guy level 5 is estimated to be approximately 1.65 m. This result differs 5 % from the result of 1.75 m, which was found using the full dynamic analysis. Based on the results from the Force-deflection diagram the maximum forces in the mast are calculated. The results from this calculation are in good agreement with values found from the full dynamic analysis.

Furthermore figure 10 can be used to find the estimate from the static approach. Since the ruptured guy is in the top level, the static force acting on the mast without the ruptured guy should be 1.3 times the horizontal force of the ruptured guy before rupture. This leads to an estimate of maximal dynamic deflection of 2.08 m, which is overestimating deflection by 19%.

Overall Design

The design of 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 is 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 crosssections, bracing configurations, profiles for structural members, etc. as this information is necessary input for the analysis. As the predominant loading of 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 (Nielsen, M.G., 1999). 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. Some antenna masts 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 situated in locations where severe atmospheric icing occurs the ice may completely block the structure so the wind resistance of the bare structure without ice does not govern the choice of both cross-section and the profiles for members.

Fig. 13: Some masts are so heavily equipped with antennas so the wind resistance of the structure itself is not so important

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

In general guyed masts are 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 parabolas shall be placed in moderate heights as well as the station have radio and TV antennas in high levels. The parabolas 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.

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 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 outmost 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.

Fig. 15: Guy attachment to foundation with tension system

Fig. 16: Mast base foundation with pinned mast bearing

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. 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.

Fig. 17: 646 m mast in Poland after failure of a guy during exchange of guy ropes

Fig. 18: 200 m mast in Sweden after insulator has broken, since lightning lit the oil in an insulator

MAST FAILURES

Guyed masts are more likely to collapse than other structures as for example towers due to the non-linear behaviour of the guy ropes. An overview over all collapses is difficult to get. However J. Laiho has created a database over the known collapses of mast and towers (Laiho, J, 1997). According to this the most common cause of failure of guyed masts is ice load (70 %), but collapses due to guy rupture appear also quite often (8 %). At least 14 collapses have been registrated by Laiho and among these was the tallest mast in the world the 646 m mast in Poland. Guy rupture can be caused by a number of events e.g. cut of guys (Aeroplanes, falling objects etc.), broken insulators (Lightning), vandalism, erection failures, deterioration of the guys (fatigue, corrosions) etc.

THE FUTURE

Even though we today have a wide knowledge of the various factors affecting the analysis, design and behaviour of masts, 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;
• aero elastic 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 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.

REFERENCIAS

EC3 Part 3-1 *(1997) “Eurocode 3: Design of Steel Structures, Part 3.1: Towers and Masts”, ENV 1993-3-1*

Bakmar, C.B. *(2004) “Wind Load on Guyed Masts”, Master Thesis, DTU*

Laiho, J, (1997) “Some known mast failure”, IASS WG4, Chicago

Leuchsenring, P., Støttrup-Andersen, U. *(1997), “Aesthetic Approach to Mast and Tower Design”, IASS Symposium, Singapore*

Nielsen, M.G. *(1995), “Comparison of Maximum Dynamic Response for Guyed Masts using four different Methods of Analysis”, IASS WG4, Winchester*

Nielsen, M.G. *(1999), “Analysis of Guy Rupture”, IASS WG4, Krakow*

Nielsen, M.G*. (2001), “Wind Tunnel Tests”, IASS WG4, Oslo*

Peil, U. *(1997) “Mast Failures - Gales and Guy Rupture”, IASS WG4, Chicago*

Smith, B.W., Støttrup-Andersen, U. *(1997), ”Towers and Masts: The Past, Present and the Future”, IASS Colloquium, Madrid*

Støttrup-Andersen, U. *(1989), “The 12 new 300 m Masts for the Danish Channel 2”, Rambøll Bulletin No .5.*

Støttrup-Andersen, U. *(2002), “Analysis and design of masts and towers”, IASS Symposium on*
Lightweight Structures in Civil Engineering, Warsaw