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50 years in the Design of Towers and Masts

From IASS Recommendations to Current Procedures

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Abstract

Up to the 1970s there were no recognized design procedures for the analysis and design of guyed masts. This was recognized in the industry in the early 1960s, when there was a rapid growth of these structures to accommodate the growth in radio and television broadcasting. Accordingly a Working Group of the IASS (WG4) was set up to examine the behaviour of these structures and to produce Recommendations for their design and analysis. These Recommendations were published in 1981 and they have formed the basis for the production of national and international codes for these structures since that date. The Recommendations contained innovative ideas at that time, including the treatment of relative structural reliability, the use of dynamic response procedures and the statistical treatment of wind actions. Such procedures have been adapted since in many design codes outside the field of towers and masts. This paper reviews the development of design procedures for both towers and masts, the background to the Recommendations and explains how these have been developed and applied in national codes (Australia, Canada, United Kingdom) and latterly in the published Eurocode for Lattice Towers and Masts.

Keywords: guyed masts, lattice towers, IASS Recommendations, Codes, Standards, wind response.

1. **History**

Whilst this paper concentrates on the past 50 years of communication structures it is instructive to consider the history of electronic communications which started over 100 years ago. Guglielmo Marconi broadcast the first transmission across the English Channel in 1899 a distance of some 50 km.

By the early 1920's public broadcasting began to develop both in Europe and in America. In 1922 a regular daily service using medium frequency broadcasting (MF) was operated in London from Marconi House and in the same year the British Broadcasting Corporation (BBC) was formed to provide a national service through operations in eight areas throughout the United Kingdom. By 1924 the total coverage by the BBC was about 65% of the population. The development of VHF broadcasting took place in the post-war years primarily due to the serious interference that occurred on MF broadcasts. By 1972 coverage by VHF/FM broadcasting in the UK reached 99% of the population.

Experimental television broadcasting commenced in the 1930s and in November 1936 a regular service began from Alexandra Palace. After the war, besides Alexandra Palace, four new stations were chosen to transmit a television service and it was estimated that these would give coverage of some 80% of the UK population. Colour transmission (on UHF wavelengths) started in 1964 following extensive tests and discussion on the appropriate systems to be adopted. Within seven years there were 33 UHF main stations and 40 relay stations in service giving the population coverage of about 91%. Digital sound for television was the next development, pioneered by the BBC, and used exclusively by about 1990. In 1996 Crystal Palace started test transmissions of digital terrestrial television, culminating in an extensive assessment and strengthening exercise for most of the major structures.

In the past few years the worldwide implementation of digital audio broadcasting (DAB) has been progressing rapidly with many countries setting up trials and launching their systems. Digital radio is the opportunity to produce multimedia radio programmes. It is possible to broadcast a range of text, graphics and even video material as well as conventional audio. This information can be displayed on a screen or a LCD display. The UK currently leads the world in the rollout of DAB systems.

The telephone was first demonstrated in 1876 but it wasn't until the 1920's that wireless mobile telephones, through radio-dispatched vehicles, were introduced. Without doubt the most significant advances in telecommunications over the past decade or so, has been the remarkable development of mobile phone services, with over four billion subscribers world-wide. Telecommunications services are a global market with over $1.5 trillion in revenue.

The global system for the mobile communications (GSM) Standard has been adopted in Europe and by more than 100 countries worldwide – but not the United States. The EU has a strong interest in establishing common standards throughout the Member States and operating companies were offered a new spectrum of frequencies dedicated to cellular services on condition that they agreed on a single standard. The United States, with a more unregulated environment which stimulates innovation, possibly suffers from multiple competing standards. In Japan the principal operating company provided a strong co-ordinating base for standardisation

Figure 1 shows the growth of communication facilities over the past 100 years, with the more rapid expansion over the past 50 years. A more extensive resumé of the history of communication structures is given by Smith in [1]

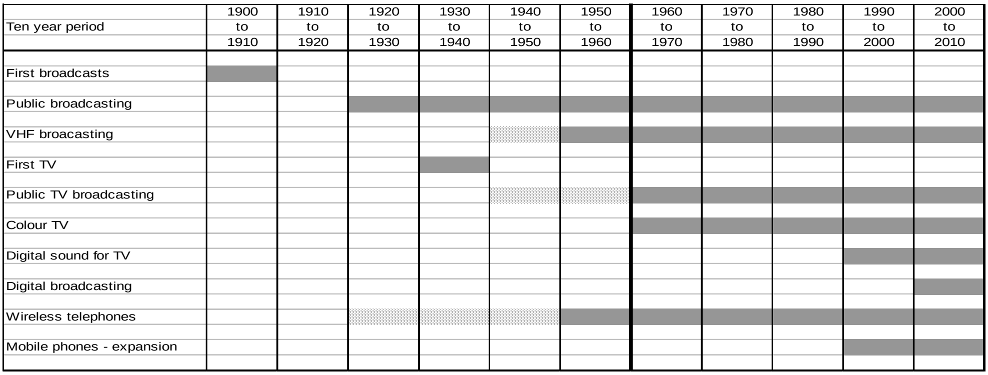

Figure 1. Growth of Communication facilities

2. Design Considerations

2.1 General

Frequently the design and construction of the antenna support structure is, in terms of costs, a relatively small element in a complex project comprising access roads, buildings, site development, transmitters, monitoring equipment, power supplies, antennas and feeders.

From a functional point of view the radio and television engineer needs antennas attached at the maximum height to a structure of minimum cross-section. This led to the advent of guyed masts which rely for their stability on sets of tensioned guys at discrete levels through the structure. It is significant to note that the 300 m high Eiffel tower weighs about 7,000 tons whereas a TV mast of the same height may weigh only about 300 tons.

Figure 2 Eiffel Tower and Guyed Mast

Over the past 50 years the most significant changes in the requirements for communication structures are probably:

a) Service requirements have changed dramatically. This has led to the development of appropriate structures to meet the electronic antenna performance requirements.

b) Environmental considerations. It is more difficult to gain approval of tall structures through the Planning Process; in particular the rapid spread of mobile phone structures in the urban and suburban environment now meets strong opposition.
c) Dynamic response procedures. It was recognized in the early 1960s that these structures are dynamic in nature and respond significantly to wind effects. Procedures to deal with this have been developed.
d) Economic considerations over a range of uses and environmental locations have lead to the acceptance of varied notional reliability and the adoption of limit state criteria.
e) Consideration of ice loading. Many masts have collapsed under the effects of heavy and asymmetric ice loads, leading to improvements in design specifications.
f) Modern fabrication techniques and the use of higher strength materials have affected the design criteria for strength assessment

Items a) and b) have dictated the form and layout of modern communication structures Items c) to f) have been considered in the development of modern codes. Each is discussed in the following.

2.2 Choice of Structure

The choice of structure is frequently dictated purely by technical requirements, but increasingly environment aspects need to be considered very carefully, particularly for major structures in environmentally sensitive areas and for small mobile phone structures to be erected in the urban or suburban environment.

The factors which determine the height and type of structure are defined primarily by the type of antenna to be used and the service area to be covered. Large aperture UHF antennas for television transmission often require a long and uniform structural cross-section of minimal face width on which dipoles or panels are directly mounted and this structural constraint generally means that a guyed mast is most suitable. Conversely the requirements of microwave link dishes demand larger face widths for mounting and a high degree of resistance to angular structural deflection under extreme wind loading, so heavier construction self-supporting towers are usually more suitable.

The antennas for DAB are generally more compact than their analogue (VHF and UHF) counterparts and so existing structures can generally be used – albeit there being the requirement for simultaneous mounting of analogue and digital antennas on structures during the introduction of DAB and phasing out of analogue broadcasting.

Mobile phone structures are generally between 10 and 30m high and a balance needs to be struck between the higher cost of monopole structures, that have the advantage of lower land costs – critical in built-up areas – and the less aesthetically appealing, but often lower cost, lattice structures. Recent designs use smaller antennas which provide the same performance but are mounted in a narrow cylindrical fibreglass shroud of less than 400 mm diameter or in a compact configuration. Such configurations allow the structure to be slender and light and tubular poles are frequently used. (See figure 3)

Figure 3 tubular mobile phone structure

Such designs not only save on costs due to the reduced wind loads but provide structures which are more acceptable to the Planning Authorities when aesthetics become an important issue.

2.3 Environmental Considerations

The environmental impact issues are perhaps one of the major aspects that need to be considered at the present time. The problem is effectively one of balance to minimise intrusion to the environment but to provide the services we have come to expect. One should also not forget that tall structures have come to be welcomed and admired. The Eiffel tower is now a symbol of Paris and the forerunner of the tall concrete towers used for broadcasting, containing observation platforms and restaurants built in many of our cities. (See Figure 4).

Planning authorities now view with considerable reservations, any applications for new towers or masts. There is an increasing lobby, for example, arguing that all transmission lines should be buried underground, despite the enormous cost implications that this would entail. The most vocal opposition is, understandably, to cellular phone structures as these are needed in urban and suburban environments where their visual impact is significant in the street-scene. Perhaps the most ingenious recent solution for the cellular telephone structures is shown in Figure 5, where the tower is disguised as a tree, constructed from tubular steel or plastic elements and camouflaged.

Figure 4 Tower in Stuttgart

Figure 5 ‘Tree’ tower

3. Response to wind

Masts and towers require special consideration in their design for the following reasons:

- They are primarily loaded by wind, which can only be described in statistical terms;
- Most, if not all, of the elements are load carrying, with little possibility of load sharing;
- They have low structural damping
- They are flexible – both for economic and functional requirement they need to be light; and
- Their frequencies are in the peak of the wind spectrum and their response is thus dynamically magnified compared with a conventional 'static' structure.

In the case of lattice towers, whose frequencies are usually well separated, the response of the structure to wind gusts is generally governed by the fundamental mode of vibration. They are linear structures and consequently can be analysed dynamically in the frequency domain. Furthermore, simplified quasi static design procedures can be adopted using appropriate gust response factors. In these procedures the peak wind load $\hat{P}$ representing the maximum load can be expressed in terms of the mean wind load $\overline{P}$, treated as a static load, by the gust response factor G_B.

Thus $\hat{P} = G_B \overline{P}$

Simple design procedures have been developed where the gust response factor depends solely on the structure's height, to which the fundamental frequency is reasonably well correlated, and the roughness of the terrain at the site of the structure.

For guyed masts, however, such a procedure may not be appropriate as the modes are not well separated and up to perhaps 15 modes can all contribute significantly to the response of the structure to turbulent winds. In contrast the first 2 modes of a lattice tower of the same height would be of interest.

A full dynamic analysis of a guyed mast is complex and time consuming. It must account for the mass, stiffness, damping and drag characteristics of the mast and guys, and the random nature of the wind. Such an analysis requires specialized computer software and a great deal of sophistication on the part of the user. Such a dynamic analysis method was developed by Davenport and his co-workers at the Boundary Layer Wind Tunnel Laboratory, University of Western Ontario [2], [3]. This type of analysis however is not practical from the point of view of routine design office use.

Considerable effort has therefore been expended in trying to produce simplifications for design rules for codes and standards. Results from a full dynamic analysis typically indicate a response (eg displacement or force) that fluctuates about a mean value. The background response is slowly varying and occurs at a frequency below the fundamental frequency. The resonant response varies rapidly and involves many modes of vibration. Most of the energy of the fluctuating wind goes into the background response.

This characteristic has been used in developing procedures which simulate a full dynamic response analysis by using static analysis through 'patch' loading techniques. [4]. In this method, a series of static load patches is used to estimate the fluctuating component of the mast response. Results from the analysis of each patch are combined in a prescribed manner, then scaled to approximate the background and resonant components.

Such patch wind models were first introduced in the IASS Recommendations for the design and analysis of guyed masts, published in Madrid 1981 [5]. Now the model has been refined and adopted in some National Codes as well as in the new Eurocode.

Several investigators have undertaken verification and calibration studies of the static procedures outlined above, against full frequency domain stochastic dynamic analyses, with robust comparisons over a wide range of structural configurations.

4. Codes and Standards

4.1 Early Codes

Other than the German Code DIN4131 [6] as far as the author is aware, there were no specialised National Standards in Europe covering the structural design of communication structures before 1980. There were Canadian and American Standards in existence however since 1965. In Europe clients tended to write project specific design criteria, calling up general design codes, for buildings for example.

Wind loading was based on general loading codes of practice. As a result the specific requirements for these forms of structure were frequently not considered. This had both positive and negative effects, as far as safety was concerned. By the 1970's most European countries introduced wind pressures representing the dynamic pressure of the wind ($0.5\,\rho\,V^2$) with maps showing appropriate isopleth contours of the reference wind speed. These speeds were then modified for the terrain and height above ground and drag coefficients for lattice frames were included in wind loading codes. However no account was taken at that time of the dynamic response of these structures in any National Standards.

None of these early codes provided any guidance on ice loading, which is the most common cause of mast failure. The procedure, at least in the United Kingdom, was to allow a nominal 12mm thickness of ice on all members in conjunction with full wind loading conditions. Such criteria neither satisfied the heavy icing that occurs in relatively low wind speeds nor the unbalanced icing on guys (with perhaps one guy uniced and two guys fully iced at any stay level) which can cause the most severe loading on the structure. Earlier North American standards failed to include ice on guys, and only considered ice on the structure.

The use of general building codes to predict the strength of the members of lattice towers and masts was unsatisfactory as these standards made little or no provision for the light slender members used in tower and mast construction nor the details used – particularly for bolted angle structures. In addition the restraints provided by the end connections – which themselves formed part of the lattice structure leading to various effective lengths - were not treated adequately in such design documents.

4.2 **Current Codes**

4.2.1 General

The absence of specific Codes of Practice or Standards for the design of tall towers and masts, certainly in Europe, was recognized in the early 1970's and developments followed to address this situation.

The International Association of Shell and Spatial Structures (IASS) held their annual Symposium in 1968 in the Hague at which specialists in the tower and mast field recognized the problems with the lack of design guidance, particularly for guyed masts, and decided to form a Working Group to embark on the drafting of Recommendations for the Design and Analysis of these structures. They published their Recommendations in 1981 [5] and these have been used as the base document for several National Standards that have been developed over the past twenty years, as well as for the Eurocode for steel lattice towers and masts.

An American Trades Body, the Electronics Industries Association, (EIA) produced their own Standard EIA-222, for steel antenna towers and antenna supporting structures. The first version of this was published in 1964 and the current version is ANSI/EIA/TIA-222-F. Revision G was published in 2005 [7] by the Telecommunications Industry Association. This Standard is adopted by the American National Standards Institute (ANSI) and it has been used internationally and considered to have international application.

The German Code, DIN4131, for steel radio towers and masts was first published in 1969 [6] and has been regularly updated – the current version was published in 1991. Czechoslovakia (as it then was) published their Standard CSN73 1430 in 1982 [8] and the United Kingdom produced a Standard for Loading of Lattice Towers, BS8100 Part 1, in 1986 [9]. The Canadian Standards Association (CSA) published their first standard in 1965 [10]. The current version was published in 2001.

Probably the development of widest significance and impact in codification is the Eurocode suite of documents, all of which have now been published. Within the Eurocode for the Design of Steel Structures (EN 1993) there is a specific Part (EN 1993-3-1) for steel towers and masts [11] – and a specific Part (EN 1993-3-2) for steel chimneys. These were published in 2006. They will be used in all the European Member Status – in conjunction with their National Annexes which provide specific information such as wind maps for the particular country. It should be noted that all National Codes and Standards in the European Community will be withdrawn in March 2010 to be replaced by the Eurocodes.

Outside Europe and North America, the Australian Standards Bodies first produced a Code specifically for towers and masts in 1991. Since then this has been revised and re-issued [12].

More details of current codes are given in Smith [1]

4.2.2 Comparison of current Codes

To show the differences in Scope between current Codes and the approaches adopted world wide, five codes are compared below. This should enable the designer to see the approaches used by Standardisation bodies, and where the philosophy and approach differs – and in some cases correspond.

What is perhaps surprising is the commonality between these Standards in both their general approach and in their detailed requirements. It is considered that this has much to do with the model IASS Recommendations [5] which has been used as a base document in developing National Standards.

Figure 6 shows the scope of each document in general terms from which it can be seen that the scope of each document is similar for loading and strength the coverage of items such as access and fabrication differ significantly.

Scope	**Eurocode**	**Australia**	**Canada**	**UK**	**USA**	**IASS**
Lattice Towers	✓	✓	✓	✓	✓	Draft only
Tubular pole structures	in separate part	x	✓	separate standards	✓	
Guyed Masts	✓	✓	✓	✓	✓	✓
Reliability classes	✓	✓	✓	✓	✓	✓
Wind loads	✓	✓	✓	✓	✓	✓
Ice loads	✓	x	✓	✓	✓	
Earthquakes	in separate part	guidance	guidance	x	✓	draft only
Roof and wall mounted structures	✓		✓	x	✓	x
Cables	✓	✓	✓	✓	✓	✓
Foundations	in separate part	✓	✓	separate standard	✓	✓
Strength	✓	✓	✓	✓	✓	✓
Fabrication	guidance		some guidance	✓	✓	✓
Erection	✓		✓	✓	✓	✓
Access	guidance	guidance	✓	x	✓	✓ separate doc
Maintenance/Inspection	✓	guidance	guidance	✓	✓	✓

Insulators	✓		✓	✓	✓	✓

Figure 6: Scope of Standards

All these Codes are presented in limit state format using partial safety factors and load combinations to assess the adequacy of the design to meet the design criteria. The EIA-TIA Standard used an allowable stress format up to the current revision, G, which has adopted the ‘load and resistance factor design’ procedure.

What is surprising is that all of the Codes define three reliability classes, a principle established in 1981 in the IASS Recommendations as shown in Figure 7.

This principle was taken on board by each of the other documents. Again this was only introduced in the EIA-TIA Standard in its revision G version. The precise definitions and classifications vary between each Code, but not to a significant extent as may be seen from Figure 8.

Class	**I - Highest**	**II – Normal**	**III - Lowest**
	All structures constructed in urban built up areas, or where loss of life could occur if they collapsed. All structures where loss of the service provided causes unacceptable danger to life, inestimable economic loss (not conforming to the parameter for economic loss set out below), or unacceptable loss of service.	All structures where the likelihood of loss of life if they collapsed would be negligible and adequate warning arrangements are incorporated to ensure that the general public are not unduly endangered. Structures where the economic consequences justify such a reduced reliability (see below). Structures where loss of the service provided is not critical and alternative means of communication can be provided.	Structures where all the consequences of failure are tolerable.

Figure 7 Reliability Classes in IASS Recommendations

Most Codes of Practice for the design and analysis of lattice towers and guyed masts use mean wind speeds as the reference velocity with a specified probability of exceedance, augmenting this by a response factor to account for the response, under turbulent wind, of the structure. In the selected Codes only the American Code retains the use of the short duration gust speed for reference, having only converted, relatively recently, from the ‘fastest mile of wind’ used through the 1960s to 1990s.

For towers and masts it is essential in any Code to be able to provide information on the effects of altitude and topography (orography as defined in the Eurocode). Invariably tall towers and masts are sited in high positions so that any increase in wind speeds to account for these effects needs to be quantified.

Code	**Highest**	**Normal**	**Lowest**
Australia	(a) the structure is designed to provide vital post-disaster communications services; or (b) the collapse of the structure and loss of the services provided causes unacceptable danger to life or extensive economic loss.	(a) the danger to life in case of collapse may be negligible and adequate warning arrangements are incorporated to ensure the general public is not unduly endangered; and (b) the loss of the services provided is not critical, e.g. where alternative means of communication can be provided.	All consequences of failure are more tolerable than those specified for Type II
Canada	Failure would result in risk of injury or unacceptable disruption of service.	Failure would result in negligible risk of injury. Loss of service is not critical.	All consequences of failure are tolerable. No foreseeable risk of injury.
Eurocode	towers and masts erected in urban locations, or where their failure is likely to cause injury or loss of life; towers and masts used for vital telecommunication facilities; other major structures where the consequences of failure would be likely to be very high.	all towers and masts that cannot be defined as class 1 or 3;	towers and masts built on umanned sites in open countryside; towers and masts, the failure of which would not be likely to cause injury to people.
UK	Determined from graph giving variable partial safety factors dependent on economic consequences and usage; three quality classes dependent on design, detailing, materials, workmanship, and inspection.		
USA	Structures that due to height, use, or location, represent a high hazard to human life and/or property in the event of failure. Structures used for essential telecommunications such as: police or fire protection; civil or national defence; emergency, rescue or disaster operations; military or navigation facilities.	Structures that due to height, use, or location, represent a substantial hazard to human life and/or property in the event of failure. Structures used for services that may be provided by other means such as: commercial wireless communications; television and radio broadcasting; cellular, PCS, CATV, and microwave communications.	Structures that due to height, use, or location, represent a low hazard to human life and/or property in the event of failure. Structures used for services that are optional or where a delay in returning the services would be acceptable such as: residential wireless and conventional 2-way radio communications; television, radio and scanner reception; wireless cable; amateur and CB radio communications.

Figure 8 Reliability classes

5. The future

There are sound reasons for believing that the huge growth of communication structures over the past 50 years is likely to come to an end.

Coverage of most countries, at least as far as conurbations are concerned, is virtually complete. New developments in electronic engineering will no doubt bring smaller and more compact antennae systems that will enable many existing structures to be used by more users simultaneously. The implementation of DAB broadcasting will provide a service whose quality would seem difficult to improve; other means of communication – satellite and cable – will reduce the need for more structures on which to mount antennas. The general political and environmental climate against building tall structures, particularly in the urban and suburban environment will make proposals for such structures more difficult to pass the planning process.

It is gratifying to note however that during the rapid expansion of communication facilities in the past 50 years, the IASS has played such a major part in setting the standards for design, analysis and construction of these elegant engineered structures.

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