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SEISMIC RESPONSE OF TALL GUYED TELECOMMUNICATION TOWERS

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ABSTRACT

The recent developments in the telecommunications industry have led to an extensive use of tall guyed towers. Very tall towers are essential infrastructures and a fundamental component of post-disaster communication systems; therefore, their protection during a severe earthquake is of major importance and accordingly the seismic performance of such structures should be properly evaluated. In this paper, the seismic behaviour of three tall guyed towers is investigated based on detailed numerical simulations. Their height is 213, 313, and 342 meters with seven, five, and seven guying levels, respectively. The main objective of this paper is to consider the overall seismic sensitivity of tall guyed towers in terms of the characteristics of their essential structural properties and the input ground motion. The results obtained from this study have so far shown that a sensitive region exists in the tower in terms of lateral stiffness which causes some nonuniformity in its seismic behaviour. Cable-mast interaction and local resonance of the cable sets at the upper levels, which are connected to the outer anchor, contribute to the response.

KEYWORDS

Tall guyed towers; seismic response; telecommunication towers; guyed antenna-supporting towers.

INTRODUCTION

In the wireless, microwave, and satellite communications industry, guyed towers are one of the important structural subsystems. They support a variety of antenna systems at great heights to transmit radio, television, and telephone signals over long distances. Guyed towers provide an economical solution for tall towers compared to self-supporting ones. The main component of these structures is usually a slender trussed steel mast of triangular cross section which is pinned at its base. Sets of inclined guy cables support laterally the mast at several levels along its height. These guy cables are pretensioned and spaced at equal angles around the mast. The various components of a typical tall guyed tower are shown in Fig. 1. The structural behaviour of guyed towers is complex; this arises from significant geometric nonlinearities due to, in first order, the sagging tendency of the guy cables, and the interaction between the cables and the tower; and in second order, the slenderness of the mast (beam-column effects). Although geometrically nonlinear effects are negligible in most structures, they are very important in guyed towers.

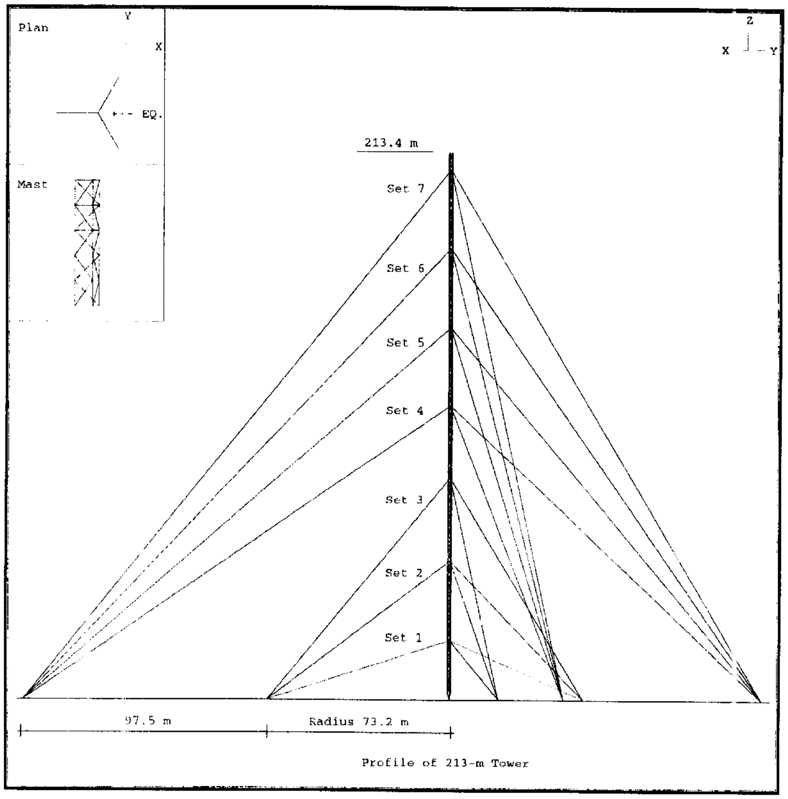

Fig. 1. Geometry of 213-m tower

Background

The structural behaviour of guyed towers has been studied by many researchers. Most of them have considered wind and ice loads on these structures, and only a few previous studies have taken into account seismic effects. The geometrically nonlinear seismic response of guyed antenna-supporting towers has recently been investigated by Guevara and McClure (McClure and Guevara, 1994; Guevara, 1993; Guevara and McClure, 1993; and McClure *et al.*, 1993). They have analyzed one tall tower (342 m) with a detailed three-dimensional truss model and two small ones (24 and 107 m) with equivalent Timoshenko beam-column models. Artificial numerical damping was used instead of structural damping. The Canadian Standards Association, in CAN/CSA-S37-94 for structural design of antenna-supporting structures, refers to the recent numerical studies reported by Guevara (1993) and Guevara and McClure (1993), and explains that geometric nonlinearities and potential interactions between mast and guy wires should be considered in a detailed seismic analysis of a guyed tower by correct modelling of inertia properties of both the mast and the guy wires. Their results have shown that vertical input acceleration amplifies the interaction between the mast and the cables. This amplification is more likely to be significant in the guy wire tensions of the top and bottom clusters.

Argyris and Mlejnek (1991) analyzed a 152.5-m transmitter tower subjected to an idealized sinusoidal earthquake loading (as a rough simulation of an earthquake). Their results indicated that computed displacements have large amplitude, and therefore serviceability conditions might be exceeded. Also, very general recommendations were made by the International Association for Shell and Spatial Structures for the seismic analysis of guyed masts, in a special report published by its Working Group 4 on masts and towers (IASS, 1981). This report suggests that a static lateral load proportional to the weight of such structures may be used to model earthquake effects, as is considered in most building design codes for base shear distributions. According to the IASS, a comprehensive nonlinear dynamic analysis of a guyed mast is unlikely to be feasible.

Research Significance

The seismic behaviour of guyed towers has received very limited attention to date. To the authors' knowledge, no simple rules have been proposed which could account for the seismic sensitivity of guyed telecommunication towers. Therefore, the researchers of this field have recommended a full nonlinear analysis under seismic load whenever the structure is located in a high-risk seismic zone and is a major installation due to its height or its relative importance in the reliability of the telecommunication network. In practice, because a full nonlinear dynamic analysis is complex and time-consuming, and because environmental loads (i.e. wind and ice) are likely to govern the design in most cases, earthquake effects are ignored in design procedures. These effects, however, may yield to a loss of serviceability due to excessive antenna displacements resulting in unacceptable signal attenuation, and in extreme cases, to permanent deformations. According to the Canadian Standards Association, CAN/CSA S-37 Antennas, Towers, and Antenna-Supporting Structures, "*earthquake effects should be considered for susceptible towers of critical importance (e.g. post-disaster communication systems) in high-risk earthquake zones*". However, in this regard, there is very little guidance in CAN/CSA S-37 for earthquake effects, and therefore in order to develop more complete guidelines, a comprehensive study on the behaviour of these structures under seismic excitation is required.

DESCRIPTION OF TOWERS

In practice, guyed towers taller than 150 m usually provide economical solutions comparing to self-supporting towers. Therefore, the lower height limitation for tall towers could be 150 m which is a common criterion to classify towers with respect to their heights. In this regard three guyed towers taller than 150 m were selected for the simulations in the finite element computer program ADINA (ADINA, 1992). They are 213, 313, and 342 meters tall with seven, five, and seven stay levels, respectively (Wahba *et al.*, 1992). The profile of 213-m tower is shown in Fig. 1 as a typical geometry for the towers. It should be noted that the earthquake direction was selected to coincide with the principal direction of mast cross section to create maximum seismic effects.

MODELLING CONSIDERATIONS

Modelling of Mast

The mast is a spatial structure with response in all three dimensions. The elements making up the masts studied are rolled steel sections. A detailed three-dimensional truss model is employed for the mast where all elements resist only axial forces. A lumped mass matrix formulation is used at the element level, and material properties are assumed linear elastic. Treating each element of the mast as a beam element with semi-rigid connections would be the most accurate model, however the more traditional solution of using truss elements has proven to provide sufficient accuracy (Gantes *et al.*, 1993). As the displacements and rotations of the mast may be large, the large kinematic formulation is considered for the mast in order to account for geometric nonlinearities.

Modelling of Guy Cables

Guy cables are modelled with three-node truss elements (tension-only). A large kinematic formulation (but small strains) is used for the cable stiffness to account for geometric nonlinearities. The stress-strain law is defined only in tension to allow for cable slackening effects to be modelled during the earthquake vibrations. The lumped mass formulation is employed in the analysis, and material properties are assumed linear elastic. It should be noted that, because these guy cables are initially pretensioned to approximately 10% of their ultimate strength, the initial stiffness matrix is always nonsingular.

Modelling of Damping

An equivalent viscous damper is used in parallel with each element to model structural damping. Since earthquake loads are assumed to occur under still air conditions (IASS, 1981), aerodynamic damping has not been modelled. Nonetheless, this model is an improvement compared to previous studies in the field. A value of 2% of critical viscous damping is used for cable and mast elements.

Input Ground Motions

In this research, three accelerograms are used in the numerical simulations. They are the S00E 1940 El Centro, the N65E 1966 Parkfield, and the S69E 1952 Taft. To simplify the discussion on the behaviour of the towers, a sinusoidal earthquake motion has been defined to represent the most probable character of these three accelerograms in terms of frequency content. The period of the sinusoidal earthquake motion was selected as 0.75 s and the amplitude corresponds to the peak horizontal acceleration recommended by the 1990 National Building Code of Canada for the Victoria region (0.34g), which has high seismic risk.

RESULTS AND DISCUSSIONS

Importance of Geometric Nonlinearities in the Response

To show the importance of geometric nonlinearities of the towers in the response, an eigenvalue analysis has been carried out in the deformed configuration under self-weight and cable prestressing forces at the beginning of the earthquake loading, and at the time the top of the tower experiences its maximum lateral displacement. Based on these analyses the period of the lowest flexural mode of the mast for each guyed tower was obtained as shown in Table 1.

Table 1. First flexural natural period of mast

Tower Height (m)	First Flexural Period of Mast (s)		Ratio
	Time = 0	Time of Maximum Lateral Displacement	
213	0.879	1.093	1.24
313	2.310	3.392	1.47
342	1.860	2.460	1.32

The ratio of the first natural periods shows the degree of geometric nonlinearity of the tower. Results indicate that the 313-m tower with five guying levels experiences more nonlinearities than the other two towers with seven guying levels.

Cable-Mast Interaction

Cable-mast interaction is a typical phenomenon of tall guyed towers. As an example, the 213-m tower has been selected to discuss this aspect of the dynamic response. As illustrated in Fig. 1, there are seven cable sets (with three cables per set) anchored on the ground at two different radii from the mast (73.2 m and 170.7 m). Figure 2 shows the time histories of vertical displacement at midpoint in one guy cable of each set with its plane along the earthquake direction. One can observe that for the cable sets at the upper levels (4, 5, 6, and 7 which are connected to the outer anchor) the natural frequency of the cable in each set is dominating the response. The overall response period corresponds to the lowest transverse mode of the cable in each set. Therefore, there is local resonance for the cables of those sets. This local resonance in the time history of cable tension appears as a beating phenomenon. Figure 3 illustrates this phenomenon in the time history of cable tension at Set 7. Another significant result is the contribution of the fundamental axial mode of the mast as a secondary effect in the response for cable Sets 4, 5,and 6. The period of this secondary effect corresponds to the first axial mode of the mast (0.11 s).

Secondary Effects in Mast Elements

The time history of axial force in the mast diagonals shows a high frequency content in the response, which is due to the lowest axial mode of the diagonals. This phenomenon happens only for those diagonals which planes are perpendicular to the earthquake direction. This effect becomes more significant with the height of the tower. Figure 4 illustrates a time history of axial force in a diagonal member at the midspan of Sets 2 & 3 in the 313-m tower. The same effect is observed for horizontal members, but appears only in the midspan sections between two stay levels, and becomes less significant for the upper levels.

Sensitive Region

For the three guyed towers studied, there are two groups of cable sets corresponding to the two groups of anchorage points on the ground. For example for the 213-m tower , Sets 1, 2, and 3 are connected to the inner anchor and Sets 4, 5, 6, and 7 to the outer one. One could then assume that there are two different parts along the mast which cause a discontinuity in the tower lateral stiffness in the transition portion from inner to outer anchor points (e.g. Sets 3 and 4 in 213-m tower). This area is therefore a sensitive portion of the tower. Figure 5 shows the variation of cable tensions, mast axial forces, mast shears, and mast moments along tower height due to the earthquake. As illustrated, there is a nonuniform behaviour around the sensitive area in each graph, confirming the above simplified model. Also Fig. 2 indicates a jump in the displacement quantities and in the overall shape of the graphs for the two groups of cable sets, which confirms the sensitivity of the transition section.

Serviceability Considerations

Antenna-supporting towers must meet strict serviceability criteria that are established by their owners in view of the particular use of the tower. Seismic amplification may affect the top part of the tower where the antennas are attached and it should not result in any local permanent deformation after the earthquake. Generally the lateral displacements along these three towers in the earthquake direction are small, in order of 0.1% of their height. This result confirms that the towers are not very flexible. It should be mentioned that due to serviceability requirements, the mast, in spite of being slender, cannot be very flexible. The displacement of the top (a usual antenna location) is small compared to that of other locations, which emphasizes the importance of serviceability at this location. Tilting of the top of the mast in each tower is less than 0.5°, which is the usual serviceability criterion for most reflector antennas.

CONCLUSIONS

The followings summarize the main results of this study:

1) Geometric nonlinearities and cable-mast interactions are important and should be simulated properly

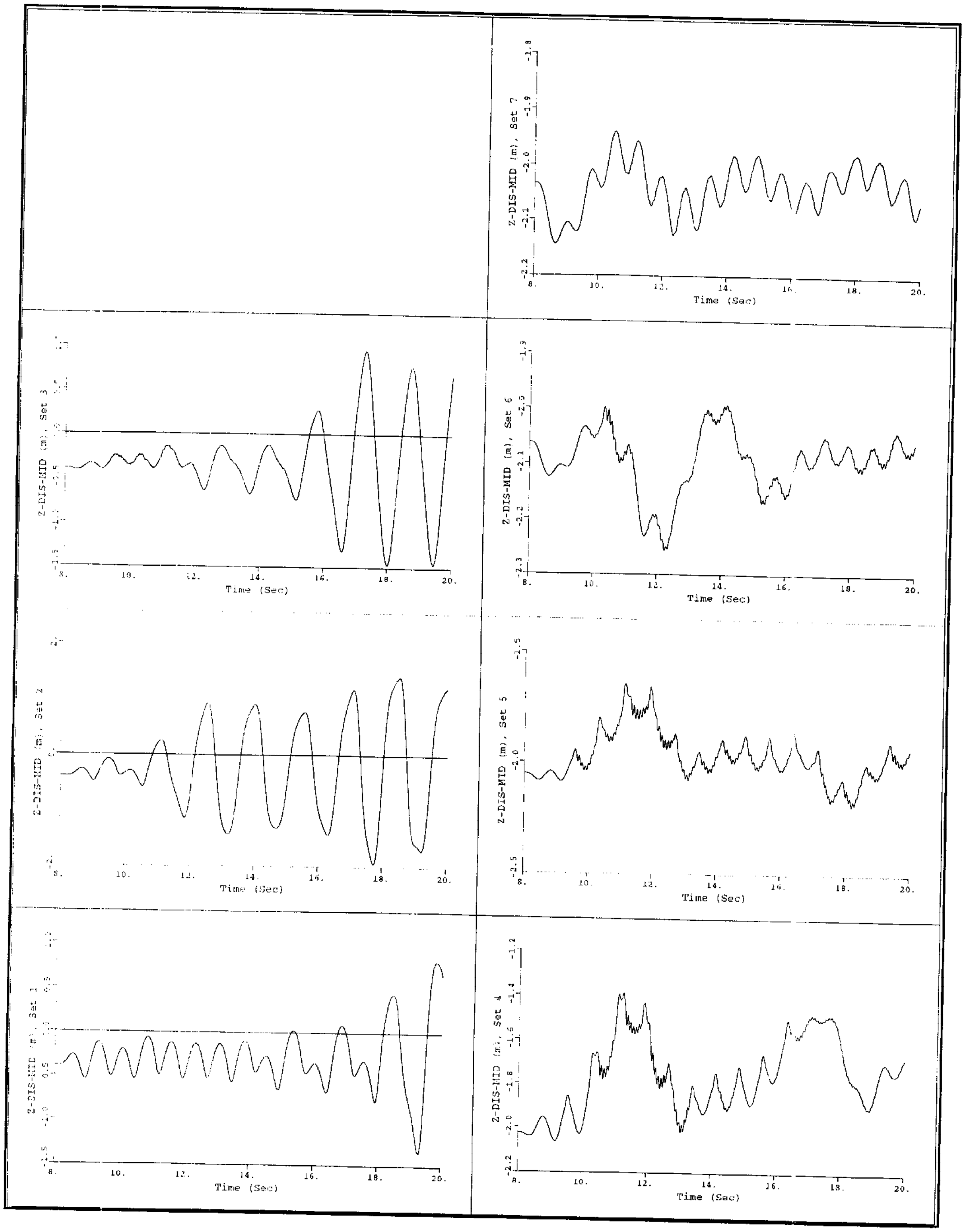

Fig. 2. Interaction of axial mode of mast in cable Z-displacement at midpoint of 213-m tower

by using appropriate type and number of elements in the cable model, suitable formulation, and also the correct modelling of inertia properties of both the mast and the guy cables.

2) Cable-mast interaction and local resonance of the cable sets at the upper levels which are connected to the outer anchor, contribute to the response.

3) There is a sensitive region in the tower in the transition portion from inner to outer anchor points. This area is connecting two different parts of the tower in terms of lateral stiffness, and causes some nonuniformity in the tower seismic behaviour.

4) The usual serviceability requirements are not exceeded for these three towers under the sinusoidal excitation.

Research Methodology for Future Work

The strategy of this research has been oriented to propose some seismic sensitivity indicators that could be used by tower designers to assess whether or not detailed nonlinear seismic analysis would be necessary. To propose such sensitivity indicators, it is needed to relate the computed detailed nonlinear seismic response to essential characteristics of the guyed towers and the ground motion. These characteristics could be the natural frequencies and mode shapes of the towers in the initial configuration or deflected shape at any time, tower height, average span between two guying levels, ratio of flexural and axial rigidity of mast, ratio of the lateral stiffness provided by the guy wires to the bending stiffness of mast, maximum ground acceleration, etc. In this regard the detailed numerical modelling study of these three guyed telecommunication towers and five others will be completed. The results will be analyzed in terms of amplitude, time at peak response, and frequency content. The conclusions drawn from this study will be used to find a simplified method to characterize the overall seismic sensitivity of tall guyed towers in terms of the characteristics of their essential structural properties and the input ground motion, and finally, to propose the seismic sensitivity indicators. Recently, a similar strategy was used in the Australian code (AS3995(Int) Interim Australian Standard, 1991) for the design of steel lattice towers and masts, suggesting that dynamic analysis under wind load is limited to those towers and masts having a fundamental natural frequency of less than 1 Hz.

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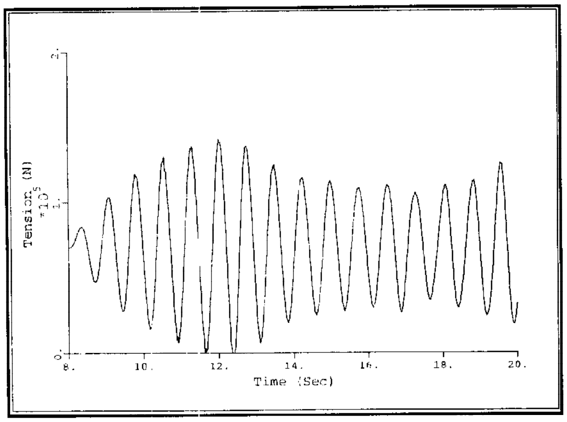

Fig. 3. Time history of cable tension at Set 7 of 213-m tower

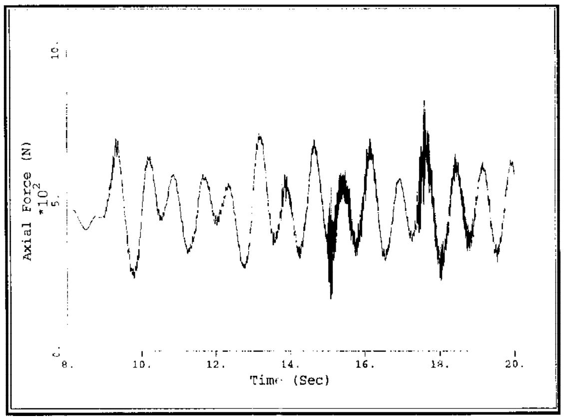

Fig. 4. Time history of diagonal axial force at Sets 2 & 3 midspan of 313-m tower

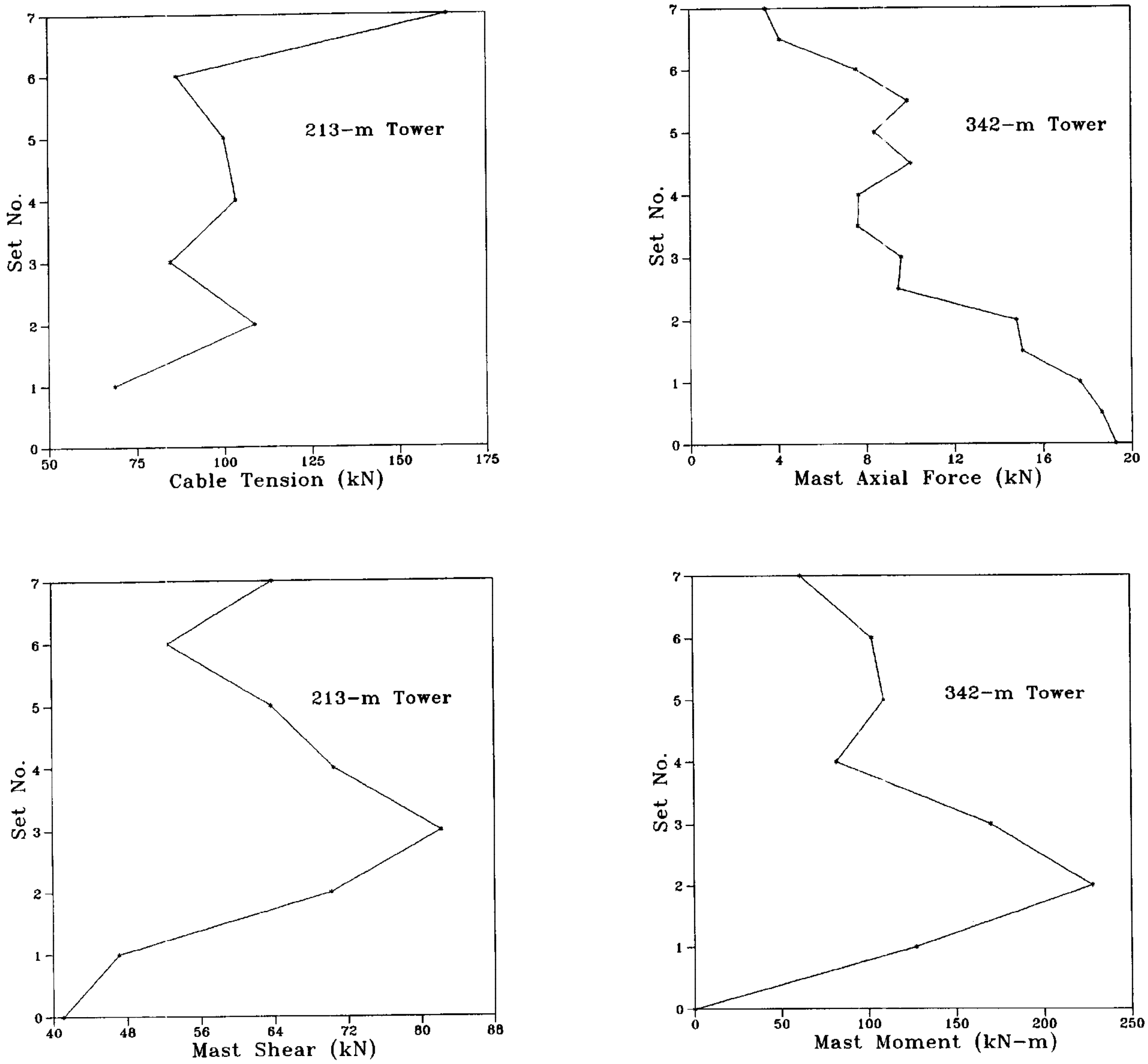

Fig. 5. Tower response due to earthquake in mast principal direction