Response of tall guyed telecommunication masts to seismic wave propagation

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ABSTRACT :

Tall telecommunication masts are slender structures whose lateral resistance is provided by clusters of guy cables anchored to the ground at several support points. The main goal of this study is to demonstrate the importance of considering realistic three-dimensional ground motion with asynchronous input when evaluating the seismic response of these tall multi-support structures. Three existing masts with heights of 213, 313 and 607 m and different guy cable arrangements have been modeled and investigated in detail with three classical historical earthquake records using a commercial finite element program (ADINA). Both synchronous and asynchronous ground shaking were considered. The effect of asynchronism in multiple support excitations was studied by varying the shear wave velocity of the surface traveling wave corresponding to different degrees of soil stiffness. The three towers have shown sensitivity to asynchronous shaking of their supports. More severe response was obtained for softer soil conditions, and the 607 m mast was sensitive even for relatively stiff soils.

KEYWORDS: asynchronous ground motion, finite element analysis, time-domain nonlinear dynamic analysis, telecommunication masts

1. Introduction

Telecommunication structures are fundamental components of communication and post-disaster networks and their preservation in the case of a severe earthquake is essential. Telecommunication masts (also called guyed towers) are typically tall (height above 180 m) structures whose function is to support elevated antennas for radio and television broadcasting, telecommunication, and two-way radio systems. Therefore, immediate serviceability or even continuous function of first-aid-station infrastructure is of critically high priority in the case of a disaster. Figure 1 illustrates a 111-m mast owned by Hydro-Québec in St-Hyacinthe, Québec, Canada, as an example.

Because of their unique geometry, telecommunication masts are categorized as slender-tall multi-support structures. As such, they are intrinsically more sensitive to some physical characteristics of earthquakes which are ignored in seismic analysis of common self-supporting structures like buildings or classical lattice towers. In particular, the effect of the spatial variation of the excitation at multiple ground support points is one aspect which deserves more attention. Until the late 1990s, the modeling procedures in commercial software did not allow to simulate direct asynchronous shaking realistically. As a result, indirect and penalty techniques were extended to compensate the simplifying modeling assumptions, such as the Relative Motion Method (RMM) [4, 12], and the Large Mass Method (LMM) [10, 13, 15] imposed on simulations. However, these methods were accompanied with some theoretical and numerical limitations. These limitations have been overcome and now it is feasible to achieve much more realistic computational simulations of tall masts under seismic loading.

Figure 1. Example of a 111.2 m guyed tower located in St. Hyacinthe, Québec, Canada

2. Background

This section reviews the simulation methods of seismic wave propagation on general multi-support structures and outlines previous applications to telecommunication masts.

Several efforts have been devoted to studying the effects of the spatial variation of ground motions in the seismic analysis of multi-support structures such as pipelines [17, 18], long multi-span bridges [6, 12], and large dams [11]. Traditional sources of information (such as seismological and geomechanics models) have been poor and unreliable in the course of producing data on spatial variation of earthquakes at the scale of engineering structures: several questionable assumptions were usually inevitable to compensate the lack of information and knowledge. The reliability of the assumptions used for the creation of input field models could only be checked with real earthquake records. Significant advances in the measurement and analysis of differential seismic ground motion have recently been obtained through the employment of arrays of strong ground motion accelerometers where a common time base allows the phases of the seismic waves to be correlated between recording elements [14]. From the study of these records, it was confirmed that spatial correlations do exist as seismic waves propagate across the array site. Further studies suggested that in the case of multi-support structures, it is reasonable to assume only a phase lag between ground attachment points and ignore the change in the general shape of the signature where there is no local fracture or landslide potential [9, 20].

Only a few researchers have investigated the influence of surface wave delays on the seismic response of tall geometrically nonlinear masts since the early 1990s: McClure and Guevara, 1993 and 1994 [10, 15], Amiri, 1997 [2], and Dietrich, 1999 [5]. The initial work by McClure and Guevara (1993, 1994) made use of the large mass method (LMM) since the ground motion could only be specified as accelerations. It was found that asynchronous ground accelerations had potentially considerable effects on the dynamic response of the structure especially in the guy cable tension of the bottom cluster. Amiri (1997) [2], concentrated on a more realistic modelling of earthquake input through 3-D field excitation simulation and concluded that several response indicators were found to be significantly influenced by the vertical components of accelerations. Later, Dietrich (1999) [5] tested an improved procedure with a short 150 m mast previously studied by Amiri. The tower was subjected to realistic three-dimensional displacement-controlled ground motion and special attention was paid to the effects of vertical ground motion as well as surface wave delays. The test was successful and confirmed the importance of involving these effects. The importance of multi-support seismic excitation of tall masts was also confirmed in a later study by Amiri et al. (2004) [3] through the investigation of the seismic response of a 607 m mast (the same as used here) and a 342 m mast which had been studied previously [2]. Faridafshin (2006) [7] has improved this research in several aspects. Only a portion of his work is presented in this paper which relates to asynchronous ground shaking effects at the supports.

3. Objective and Methodology

The main goal of this study is to clarify some of the previous results and attempt to identify more definite trends in the calculated response of tall masts subjected to realistic three-dimensional ground motion. Three existing masts with heights of 213, 313 and 607 m and different guy cable arrangements have been modeled and investigated in detail using the commercial finite element program ADINA [1]. Following a series of simulations modeling the earthquake excitation as synchronous shaking, the effect of asynchronous input was considered assuming the tower on different site conditions with various surface shear wave velocities.

4. Guyed Tower Models

The geometric characteristics of the three masts are summarized in Table 1 and a schematic of the 607 m mast is illustrated in Figure 2 to provide an example. More information on the geometry of the masts is available in [7]. It is noteworthy that the 607 m mast is among the tallest man-made structures and is located in Sacramento, California.
Seismic loading is specified with three classical earthquake records representing different frequency contents. The information related to earthquake loading is summarized in Table 2. The 1940 Imperial Valley (El Centro) Earthquake represents an input with a wide and rich frequency range and several episodes of strong shaking. The 1952 Kern County (Taft) Earthquake has high frequency content and strong shaking with long duration. Finally, the 1966 Parkfield Earthquake represents a single pulse loading with dominant lower frequencies. An additional motivation for selecting these three classical records was the opportunity to compare the results with those generated by Amiri (1997) [2].
More details on the finite element models can be found in Faridafshin (2006) [7] and Faridafshin and McClure (2008) [8].

Table 1. Geometry of the three masts studied

Height (m)	No. of stay levels	No. of anchor groups	Panel width (m)	Panel Height (m)
607.1	9	3	3	2.25
313.9	5	2	2.14	1.52
213.4	7	2	1.52	1.52

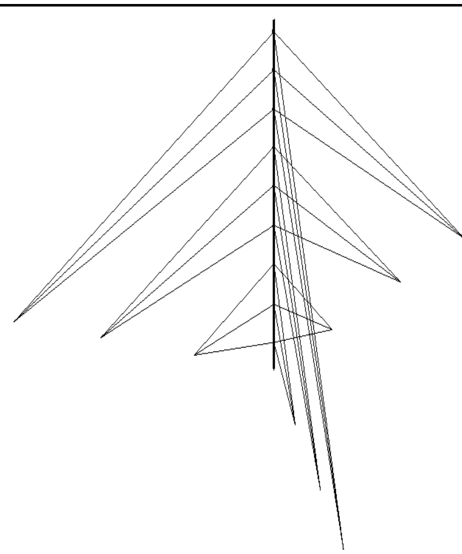

Figure 2. Geometry of the 607 m mast.

Table 2. Earthquakes from PEER - Pacific Earthquake Engineering Research Center database [19].

Earthquake	date	Magnitude (M)			Station	Site condition (USGS)
		M	MI	Ms		
Imperial Valley (El Centro)	5/19/194	7.0	-	7.2	117 El Centro Array #9	(C)
Kern County (Taft)	7/12/1952	7.4	-	7.7	1095 Taft Lincoln	(B)
Parkfield	6/28/1966	6.1	6.1	-	1014 Cholame #5	(C)

5. Modelling asynchronous ground motion

According to principles of soil dynamics [20], there are three general causes for changes in the shape of the surface wave as it traverses the supports of a structure. First of all, if the material properties of the soil along the propagation path exhibit large variations between supports, it is expected that the wave shapes at the two stations would also differ. Secondly, localized wave reflections and refractions can cause changes in the wave shape. Thirdly, various types of seismic waves travel at different speeds, and for surface waves, the speed is a function of frequency. The time lag between two stations is not the same for different components of the seismic excitation, leading to changes in the wave shape. Seismic waves also attenuate as they propagate away from their source. However, for telecommunication masts, the concern is not the change in the shape of the surface wave because the footprint of these structures is not large enough to trigger significant variations in wave velocities or attenuation effects. It is therefore reasonable to assume that the spatial variation of the seismic excitation can be modeled as a travelling wave having a signature which remains unchanged as it traverses the structure. The effective velocity of seismic waves is of the same order as the shear wave velocity of the underlying soil [20]. Thus, the wave travel time from one support point to the next is then simply calculated from the ratio of the distance between the supports and the shear wave velocity. This is illustrated schematically on Figure 3 for the 607 m mast. In this study, the site conditions (soil type) with their corresponding shear wave velocities are based on the classification of the National Building Code of Canada (NRC/IRC 2005) [16] and are represented schematically in Figure 4.

A series of synchronous ground shaking simulations were run for each mast to provide a reference basis for comparisons. The complete results are presented in [7]. Then various asynchronous shaking scenarios (each with a specific shear wave velocity) were modeled to identify the shear wave velocity threshold at which asynchronous motion started to significantly influence the response. The four boundaries between the site classes defined in Figure 4 (i.e. $\overline{V_S}$ = 180, 360, 760, 1500 m/s) were first considered to determine the sensitivity range for each tower. Then these intervals were successively reduced until the threshold value of shear wave velocity was identified.

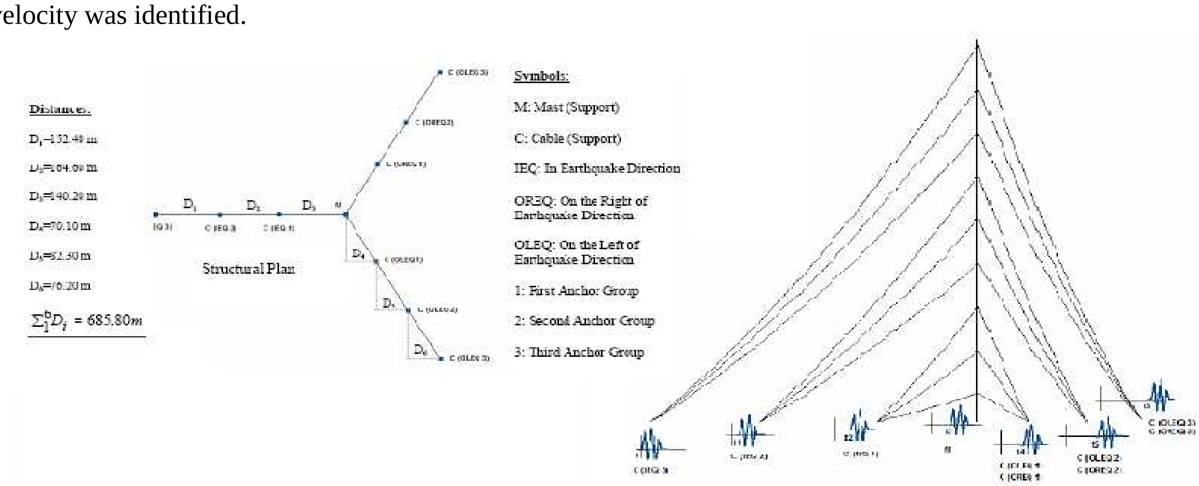

Figure 3. Schematic asynchronous ground motion input at supports for the 607 m mast.

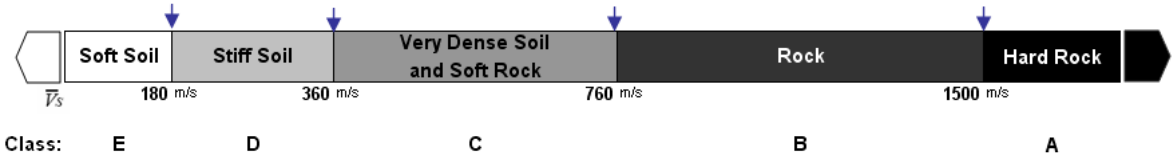

Figure 4. Soil categories and shear wave velocities according to NBCC 2005 [16].

6. Results and Discussion

Figure 5 is a schematic summary of the results of all the simulations for the three towers. The arrows on the figure show the discrete velocities selected based on a bi-sectioning algorithm between the boundaries and taking into account the sensitivity and accuracy considerations.
For the 213 m and 313 m masts, the influence of asynchronous shaking initiated on stiff soil conditions. For the 607 m mast, however, the effect is significant in a much larger range of soil conditions, starting in very dense soil and soft rock, even toward the boundary for rock, as shown in Figure 5.
For the tallest mast, a similar trend is observed in almost all response indicators. When the shear wave velocity and consequently the time lag between the support excitations increase, greater response is obtained in the structure. The mildest case is ST660, (e.g. ST660 corresponds to the soil type with shear wave velocity of 660 m/s) while the most severe case is ST180 which represents the boundary of soft soil. When the structure is founded on soft soil - which is usually avoided, very severe response may result for most of the response indicators. Figure 6 presents the envelopes of some typical response indicators: cable reaction forces on the mast, shear forces and bending moments in the mast. The general trend is to have a larger response when moving toward a softer soil. However, exceptions might exist at some guying levels as shown for instance on Figure 6 for the horizontal component of cable reaction forces on the mast between the elevations 100 and 300.
Another interesting finding is that for all three towers, the maximum responses typically occur in the very beginning of the ground shaking when one side of the tower is vibrating and the excitation has not started in the other parts. This impulsive response indicates that these structures are more vulnerable to out-of-phase shaking that is indeed more similar to the nature of earthquakes. This is illustrated in Figure 7 showing the time history of the cable tension in a guy wire for a synchronous analysis compared to an asynchronous simulation.
Antenna-supporting structures must meet strict serviceability criteria that depend on their particular function. Seismic amplifications of displacements and rotations will affect the mast during strong shaking, but they should not result in any local permanent deformation if immediate functionality is required after the earthquake. In the study, all the towers appear to behave within reasonable serviceability limits in the case of synchronous shaking. But this is not the case under asynchronous excitation. Figure 8 depicts the horizontal displacements of the 607 m mast under the Taft input where it is seen that asynchronous shaking has an important amplification effect on the mast translations, especially in the case of softer soils.
Figure 9 illustrates the envelope values of the force and moment response of the 313 m mast. In general, trends in behaviour appear similar to those observed for the 607 m for most of the response indicators. When the shear wave velocity and consequently the time lag between the support excitation increases, greater response is obtained in the structure.
Results are not shown for the shortest mast (213 m) for conciseness. As expected, however, the effects of asynchronous shaking are not as important or as systematically related to shear wave velocity as in the previous two cases.

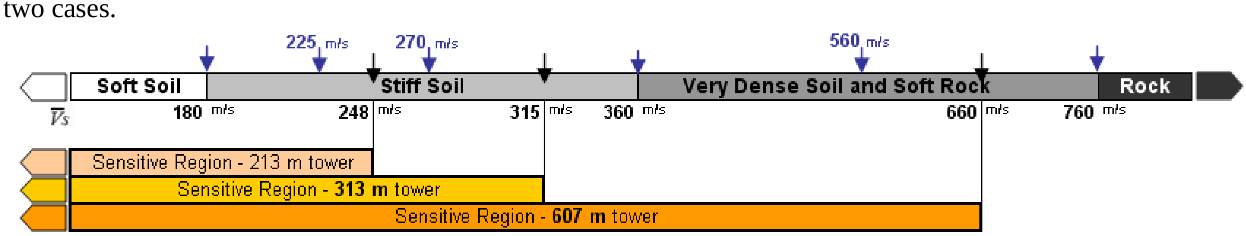

Figure 5. Sensitivity to asynchronous shaking in relation to the shear wave velocity of the soil.

7. Conclusions

The displacement-controlled approach for the modeling of earthquake loading has enabled the modeling of asynchronous ground motion in a straightforward manner. Time-domain nonlinear dynamic analyses were run using three historical earthquake records and the shear wave velocity of the supporting soil was varied to calculate realistic arrival time delays of the excitation at the support points. The main findings are:

- Different earthquake records with diverse scenarios of motion may produce quite different responses in the structures and the use of several records appropriate to the seismicity of the tower site is therefore necessary.
- The three masts showed sensitivity to asynchronous shaking of their ground supports. Concerning the site condition, the sensitivity of the 213, 313, and 607 m masts to asynchronous shaking initiated on underlying soils with 248, 315, and 660 m/s of shear wave velocities respectively. The first two velocities fall in the category of 'stiff soil' while the sensitivity of the 607 m tower has been triggered in the site class 'very dense soil and soft rock' according to NBCC 2005.
- The taller the structure, on a softer soil the sensitivity to asynchronous shaking has initiated. The boundary of soft soil ($\bar{V}s$ = 180 m/s) has yielded very important amplifications of the response and the construction of important tall masts on site classes with low shear wave velocity is certainly to be avoided.
- A general trend that can be seen in almost all response indicators in the analyses with asynchronous shaking is the increase in the response when the shear wave velocity decreases and consequently the time lag between the support excitations increases.
- For the three towers studied, the peak response most often occurred in the very beginning of the ground shaking when one side of the tower was vibrating and the excitation had not started in the other parts.

Considering the computational modeling capabilities now available in engineering practice, the authors recommend that nonlinear seismic analysis of tall guyed masts include coherent ground motion records and asynchronous shaking at multiple support points.

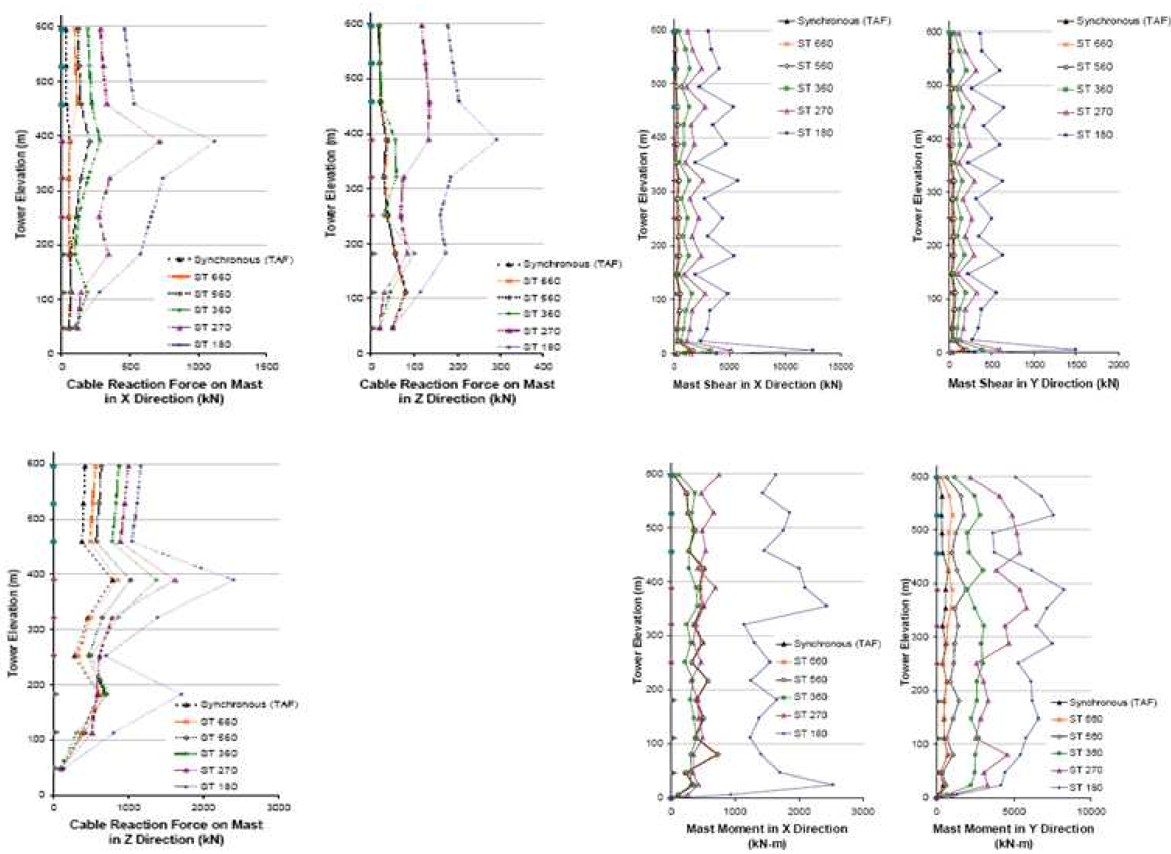

Figure 6. Envelope of force and moment response indicators; Taft record; 607 m mast

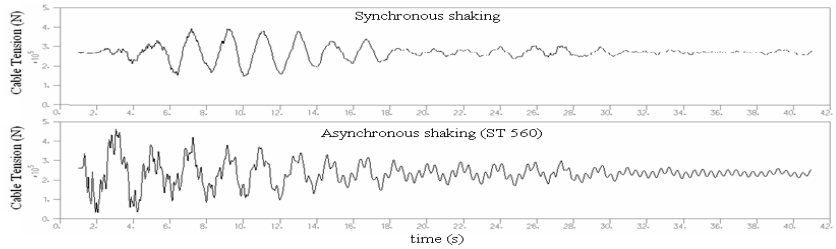

Figure 7. Effects of synchronous vs. asynchronous shaking on the time history of a guy cable tension in the 607 m mast. The tension shown was obtained for a cable element of the sixth guying cluster from the base, at the lower third of the cable length.

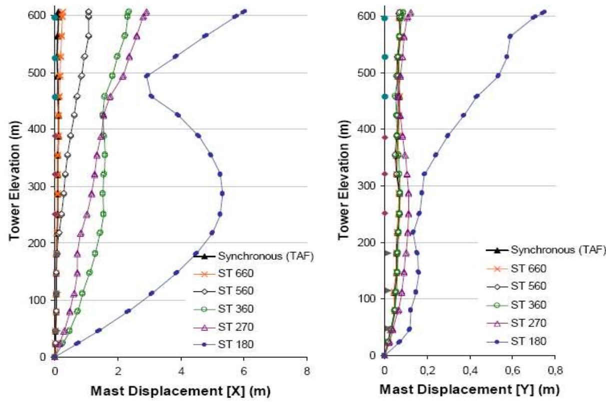

Figure 8. Envelope of horizontal mast displacements in X and Y directions; Taft record; 607 m mast.

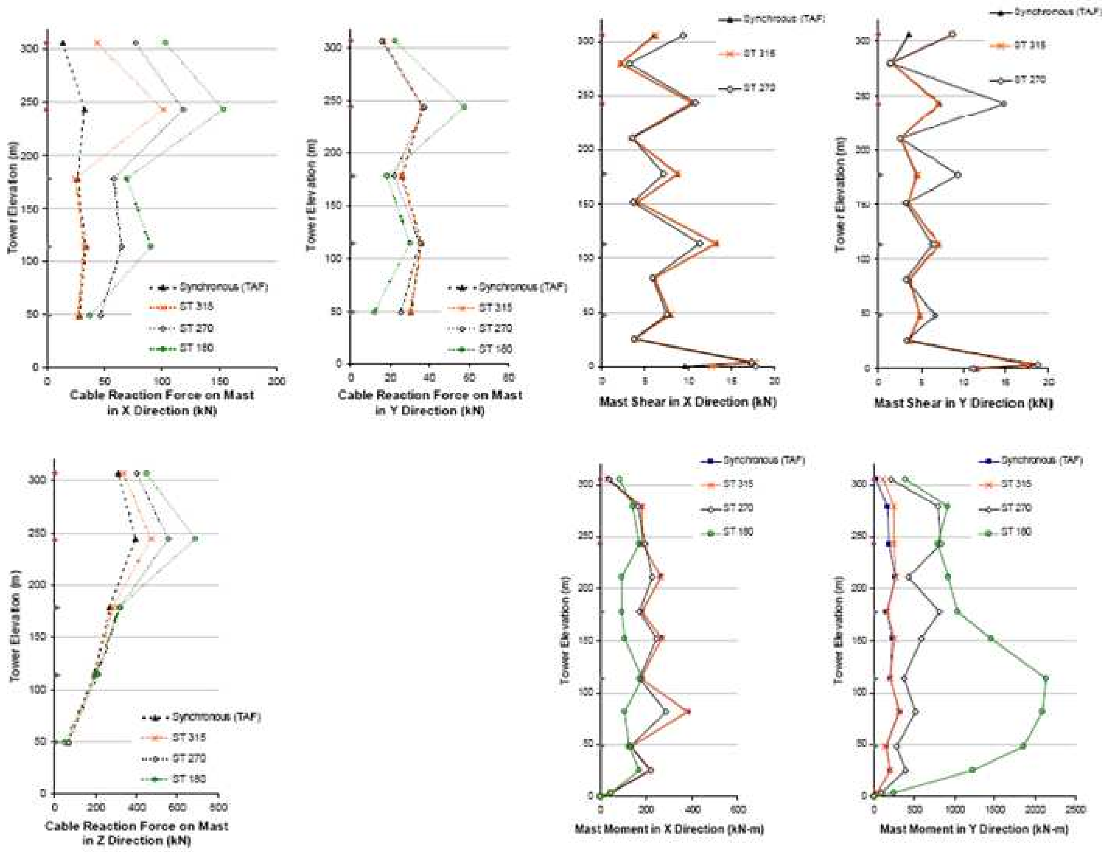

Figure 9. Envelope of force and moment response indicators ; Taft record; 313 m mast

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