Assessing the variability of seismic response analysis of a tall guyed telecommunication tower with ambient vibration measurements

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SUMMARY:
Many telecommunication structures are designated as post-critical facilities that must remain operational after a design-level earthquake has struck. Despite of conducting several detailed numerical studies with care and expert knowledge on tall masts, there are some concerns about the degree of certainty of these studies. The goal of this project is to provide a case study of experimental validation using ambient vibration measurement tests for evaluating the accuracy of numerical studies. These tests were done on a 111.2-m tall mast owned by Hydro-Québec and located in St. Hyacinthe, Québec, Canada. The dynamic properties of the guyed mast extracted from AVM records are compared with those obtained from nonlinear finite element analysis models. The first few natural frequencies of the structure obtained from adjusted finite element models are compared with those obtained by AVM identification and show agreement. Finally, a series of earthquake simulations on the "verified" model explore the influence of cable tension variability on a few salient tower response indicators.

Keywords: Telecommunication tower, Guy cable dynamics, Dynamic analysis

1. INTRODUCTION

Telecommunication structures are fundamental components of communication and post-disaster networks and their serviceability immediately after a design-level earthquake is essential. In fact accessing to telecommunication and broadcast services is one of the main advantages of using telecommunication masts especially in emergency situations like after a severe earthquake. Telecommunication structures are also used for automatic control of electric power networks, which makes them all the more strategic for lifeline serviceability. Several published studies have used detailed nonlinear dynamic analysis of tall guyed masts using finite element models, either to predict the response of specific structures or to develop simplified analysis procedures more amenable to design practice. Some of these studies are mentioned in the reference section: Guevara and McClure, 1993; Kahla, 1994; Amiri and McClure, 1996; Madugula *et al*. , 1998; Amiri, 2002, Meshmesha *et al.* , 2006;. The recent work of Ghafari Oskoie and McClure (2011 and 2012) proposed a simplified seismic analysis procedure based on the evaluation of the equivalent horizontal dynamic stiffness of guy clusters supporting the mast. Although the procedure was extensively validated with comparative numerical models, no *in situ* experiments were done to quantify the variability expected from the model simplification of the actual structural mast properties. In particular, the authors were concerned that the variability in guy cable tensions in the field, compared to nominal design values specified at a reference temperature, needed to be addressed in analysis. This is the main goal of this study. This study therefore combines experimental and computational approaches. The first step was to conduct ambient vibration measurements on a guyed mast to extract its structural dynamic properties (natural frequencies, mode shapes and estimates of modal damping), and to monitor precisely the ambient response of individual sets of guy cables to extract their average tension. The computational study proceeds with detailed finite element models of the mast that have been updated based on the *in situ* cable tension results, and examines the effect of the variability in guy cable tension on the calculated seismic response. Since the goal here is to assess the variability of seismic response given one parameter (guy cable tension) the earthquake input was kept the same for all simulations and the El

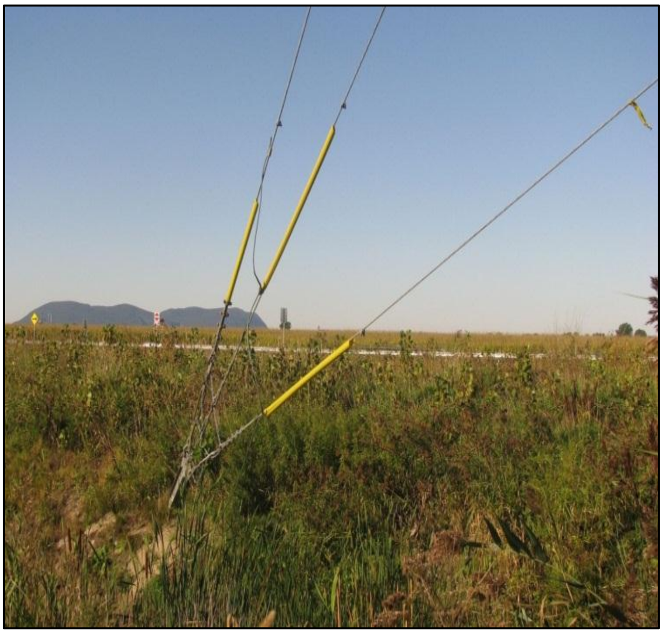
Centro (1940 Magnitude of 7.2 Ms) horizontal and vertical accelerograms measured at Station 117 of Array #9, were selected.

Two variants of tower models were considered in seismic analysis, excluding and including the additional weight of antennas and transmission lines attached to the mast structure.

The tested structure is a 111.2-m (365 ft.) tall telecommunication mast owned by Hydro-Québec and located in St. Hyacinthe, Québec near Highway 20. It was constructed in 1978. Figure 1.1 shows the general layout of the tower and some structural details.

a) General layout

b) Mast pinned-base connection



c) Antenna attachment to the tower

d) Cable attachment to the ground

Figure1.1. 111.2-m guyed telecommunication mast in St. Hyacinthe, Québec

The mast (Figure 1.1 b) has triangular cross section with panel dimensions of 1.116 m (3’-8”) in width and 1.02 m (3’-4”) in height. It is supported laterally at six stay levels arranged at two ground anchor groups, at distances 39.6 m (130 ft.) and 83.8 m (275 ft.) from the mast axis. The general layout is also illustrated schematically in Figure 2.2.

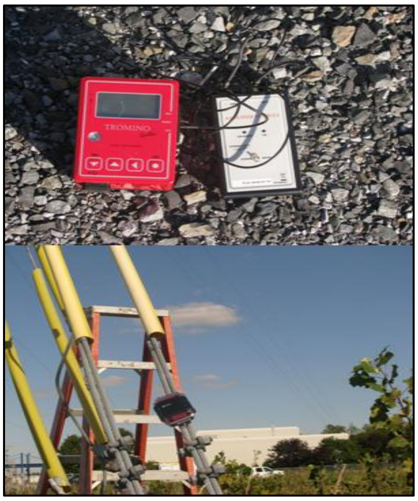
2. AMBIENT VIBRATION TESTING PROCEDURE

The test was carried out on 19 September 2011, with the assistance of linemen from Hydro-Québec (Figure 2.1 a). Two types of AA-battery powered instruments have been used for AVM data collection: TROMINO ENGY PLUS™ tromographs (see www.tromino.eu) and GP1 accelerometers (see www.sensr.com) (Figure 2.1 b). These sensors were easily synchronized to each other by a radio communication system. The tromographs were used for measuring the velocities of the mast at selected elevations and the GP1 accelerometers were placed on the guy cables to determine their average tension.

The test proceeded in two stages. At the first stage, the seven tromographs were installed at selected mast elevations and six different recording episodes were taken, of duration varying between 6 to 10 minutes. Afterwards, the tromographs were left in their location (and in recording mode) and the second stage was started where measurements were made on the guy cables using the GP1 accelerometers. Three GP1 sensors were installed on each guy wire separately: one near the cable top attachment point to the mast, one near the ground anchor, and the last one about 1 meter higher than the sensor near the ground anchor. The recording episodes with the GP1 accelerometers lasted approximately 4 to 5 minutes.

GRILLA™ software (supplied with the tromographs) was used for transferring the collected data from the sensors to the laptop computers and carrying out data truncation and synchronization based on the time stamps in the individual data files. Identifying the dynamic characteristic of the dynamic structure (natural frequencies, mode shapes, damping) was done using ARTeMIS™ Handy extractor (http://www.svibs.com/products/ARTeMIS_Extractor.aspx). This software offers different methods for natural frequency and mode shape identification, and the Enhanced Frequency Domain Decomposition (EFDD) method was selected.

a) Linemen setting up tromographs in the mast



b) Tromograph and radio communication antenna (top) and GP1 accelerometer attached to guy wire (bottom)

Figure 2.1. Tower instrumentation

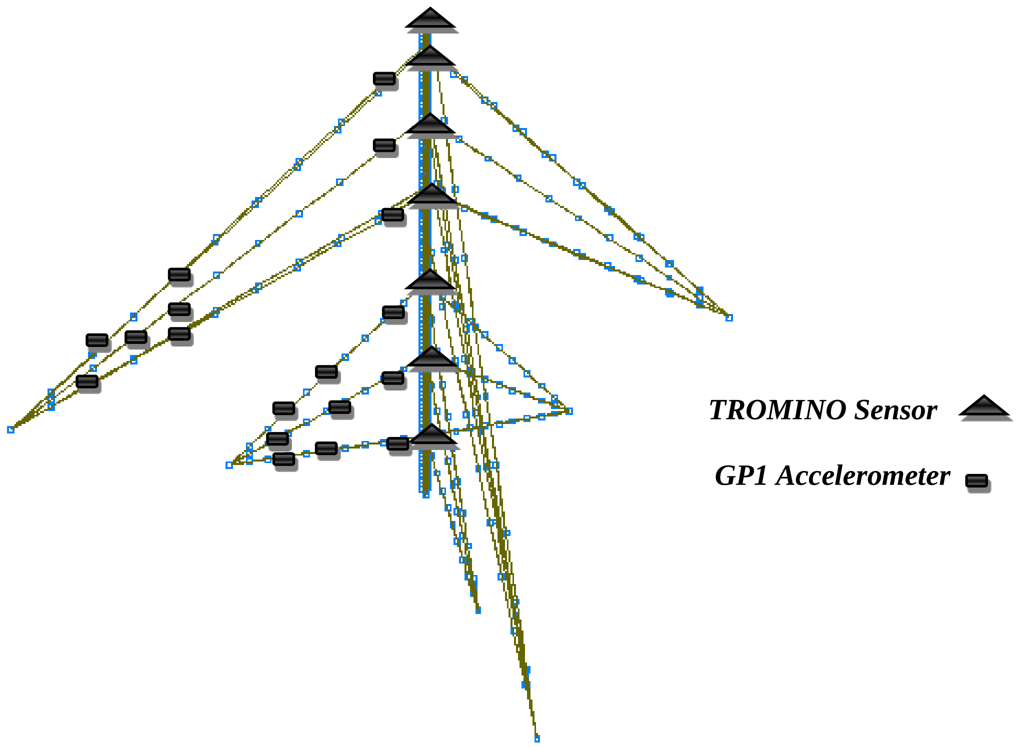


Figure 2.2. Location of the sensors on the tower

3. RESULTS

3.1. Dynamic Characteristics

Due to the limited number of tromographs (7 in total; one on the ground) installed in the mast, it was possible to determine the first three (lowest frequency) horizontal modes of the structure. These dynamic characteristics and the fundamental frequency of each tested guy wire were verified. Since the AVM tests were conducted from morning to afternoon and on a sunny day, there was significantly variation of temperature during the day. Cable tensions calculated from the measured frequencies correspond to the ambient cable temperature during the test. For the purpose of comparing the experimental results of the whole guyed mast with the computational results, the cable initial tensions in the guyed tower models have been adjusted by considering the experimental results at 24°C, which was deemed representative of the average ambient temperature for the different recording episodes.

As mentioned above, the experimental fundamental frequency, f_o, of each cable is used to determine an estimate of the guy wire tension in view of updating the finite element model of the tower. The average cable tension (T_{av}) is approximately determined using the fundamental frequency equation of a taut string (out-of-plane symmetric mode):

$$T_{av} \approx 4\, m L_c^2 {f_o}^2 \qquad (3.1)$$

where m is the mass per unit length and L_c is the chord length. Three values were found for each cable since three sensors per cable were installed. There were some temperature differences between the top and bottom cable sensors and also during the measuring episodes so their average temperature was considered when calculating individual cable tensions. Table 3.1 indicates the calculated cable tensions and corresponding average temperatures: these tensions are calculated using Eq. (3.1) with the experimental frequency values listed in Table 3.3; the detailed nominal properties of the guy wires are also listed in Table 3.3, noting that they are numbered sequentially from top to bottom.

Table 3.1. Calculated cable tensions at average temperature

Cable #	Average cable temperature	Calculated tension (Eq. 3.1)
	(°C)	(kips / kN)
1	24	4.19 / 18.6
2	25	7.33 / 32.6
3	26.5	5.97 / 26.6
4	27	5.63 / 25.0
5	31	3.32 / 14.8
6	30	NA

It is noted that the natural frequency of Cable #6 was not clearly identified due to a noisy AVM record and therefore its cable tension could not be determined: this is the shortest cable of the structure and its tension was relatively large, resulting in high natural frequency. Therefore, in the numerical models, only the cable tension based on the nominal design value is used for Cable #6. At this stage, the FE model was updated with the calculated cable tensions based on field frequency measurements. The effects of cable tension adjustments on the natural frequencies of the structure are shown in Table 3.2 by comparison of the values predicted with and without adjustment. The updated model with bare mast has slightly lower frequencies than the nominal model and is in excellent agreement with the average experimental values. One further model refinement was to include the added weight of the antenna drums and transmission lines running along the tower inside the mast. However, the weight of the ladders and rest platforms were not added. It is seen that this added mass further decreased the lower natural frequencies of the mast only very slightly (the effect is in the order of 1% only).

Table 3.2. Comparison of experimental and numerical natural frequencies of the guyed mast

Vibration Mode	Natural frequency (Hz)			
	Experiment	Nominal FE model at 20°C	Updated FE model (bare mast) at 24°C	Updated FE model (with equipment) at 24°C
1	1.5 ± 0.06	1.80	1.59	1.57
2	1.9 ± 0.10	2.11	2.01	1.99
3	2.4 ± 0.14	2.52	2.46	2.46

Table 3.3 summarizes the results obtained for the fundamental frequencies of the guy cables. Since the antenna mass distribution is not uniform along the mast (see Fig. 2.1 a), the effects of these additional lumped masses do not have a uniform trend. The updated FE model with equipment yields cable frequencies closer to those of the experimental results when compared to the bare mast. For the top cluster, for example, the bare mast updated model yielded a frequency 20% below the experimental result while the more realistic model overestimates the experimental frequency by about 10%. Except for Cluster #2, the effect of the added masses on the cable frequencies is significant, with the calculated frequencies overestimating the experimental values by approximately 15 to 20%. The effects are more evident on the initial cable tensions reported in Table 3.4. Although adding attachments did not have much effect on the cable initial tension of most cables (except the top cluster), the accurate seismic analysis models are those where the cable tensions are modelled more accurately. The top cluster (Cable #1) comprises the longest cables and adding the attachments below it reduces its initial tension considerably. Although cable tension variability does not significantly affect the lower frequency modes of the mast, it is expected to affect the mast response, which is clearly seen in the time histories of Figures 3.1 to 3.3.

Table3.3. Comparison of experimental and numerical fundamental frequencies of guy cables

Nominal cable properties					Fundamental frequency (Hz)			
#	Stay elevation (m)	L_c (m)	A (cm^2)	W (kg/m)	Experiment	Nominal FE model at 20°C	Updated FE model (bare mast) at 24°C	Updated FE model (with equipment) at 24°C
1	104.14	133.68	1.226	0.982	0.51	0.538	0.407	0.547
2	87.88	119.11	2.181	1.756	0.57	0.534	0.561	0.567
3	65.13	109.57	1.510	1.220	0.67	0.596	0.672	0.672
4	49.28	63.21	2.554	2.068	0.87	0.95	0.825	0.866
5	32.00	50.93	1.510	1.220	1.08	1.22	1.066	1.07
6	13.72	41.94	1.226	0.982	NA	1.54	1.514	1.54

Table3.4. Initial cable tensions prescribed in the FE models

	Initial cable tension (kN)		
Cable #	Nominal FE model at 20°C	Updated FE model (bare mast) at 24°C	Updated FE model (with equipment) at 24 °C
1	12.7	17.8	12.3
2	29.4	32.0	31.9
3	20.4	25.8	25.7
4	29.1	21.6	21.4
5	18.3	13.7	13.6
6	15.7	15.2	15.2

3.2. Seismic Response Analysis

In this part of the study, the variability of the seismic response of the tower is examined by considering three different finite element models of the structure, namely: a FE model with nominal design properties at 20°C, and two FE models modified to a include realistic cable tensions based on the AVM test results, at 24°C. The difference between these two modified FE models lies in the addition of the weight of antennas (mostly located in the vicinity of Cluster #2) and transmission lines in the more accurate model, while the other one represents the bare mast structure.

The seismic analysis proceeds with the El Centro horizontal accelerogram aligned in a principal direction of the mast (X direction, along one set of guy cables) and the corresponding vertical accelerogram. This input is assumed synchronous at each support point, i.e. at all cable ground anchor points and at the base of the masts, assuming all support points to be rigidly fixed. This earthquake record has a peak horizontal ground acceleration of 0.33 g, a peak ground velocity of 29.8 cm/s and a peak ground displacement of 13.32 cm; in the vertical direction, the peak ground motion values are of 0.215 g, 30.2 cm/s and 23.91cm, respectively.

Figures 3.1 and 3.2 show the computed time histories of the mast displacements at the elevation of the bottom cluster attachment point (13.72-m) and at the top cluster (103.94-m), respectively. The response indicators reported in the Y direction simply correspond to the transverse orthogonal direction to X (input direction). As expected, the ground displacements are amplified at the top cluster elevation compared to the bottom. In keeping with the natural frequency results reported earlier, it is seen that the response predicted with the added weight of antenna drums and transmission lines is actually closer to that predicted by the nominal model.

Figure 3.3 shows the dynamic cable tension in the top cluster: in this case, however, the bare mast model is far from the measured frequency and its predictions are not expected to be accurate. In reality, the nominal design guy wire pretensions used in analysis are practically never achieved when the mast is constructed. This does not pose any practical problem as long as the overall structure stays within prescribed tolerances and fulfils its functionality requirements. As these structures are exposed to the natural environment, wire tensions will vary considerably with ambient temperature, direct exposure to sunlight, and ambient climatic loads (wind and ice).

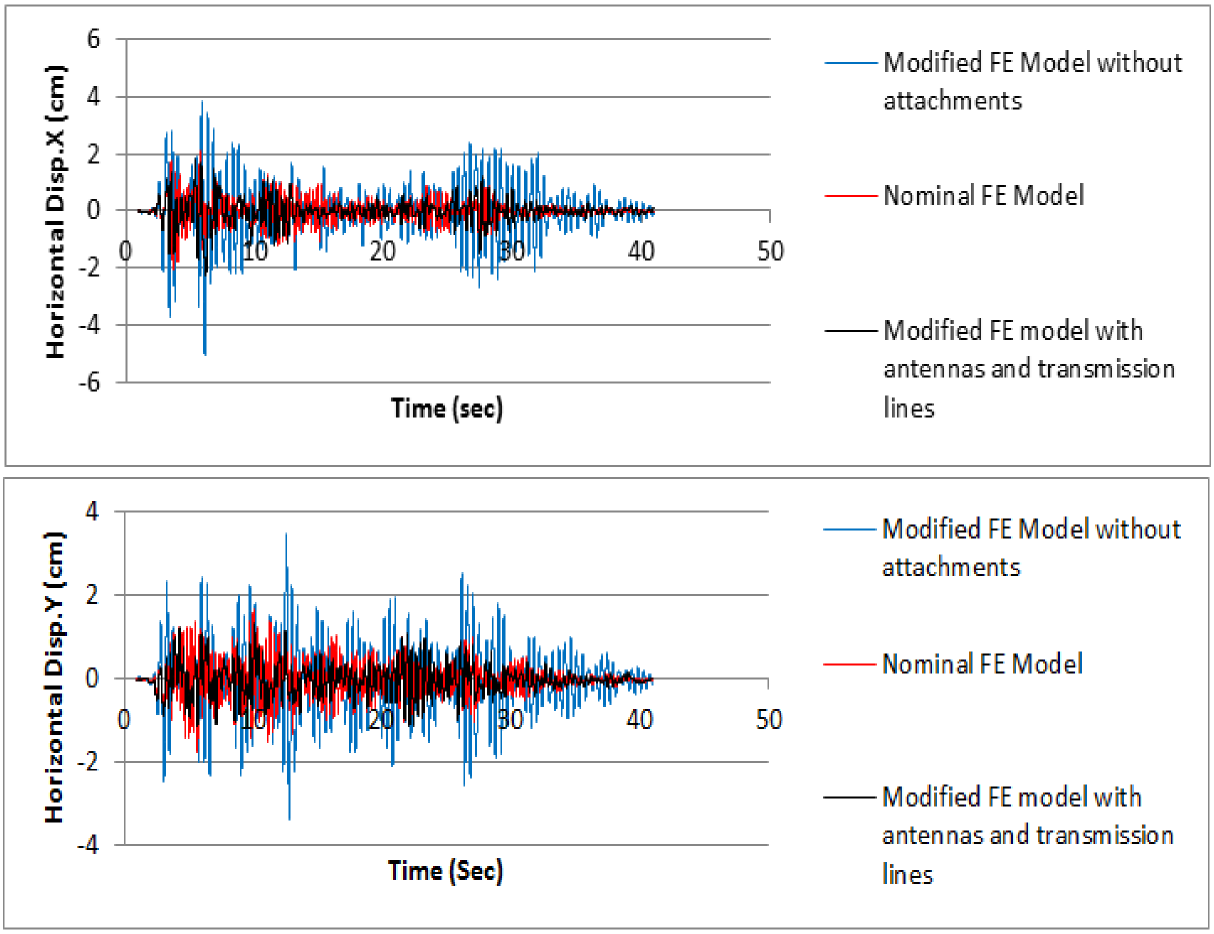


Figure3.1. Horizontal displacements of the mast at cable cluster elevation #6 (bottom cluster) along the X (along input) and Y (transverse to input)

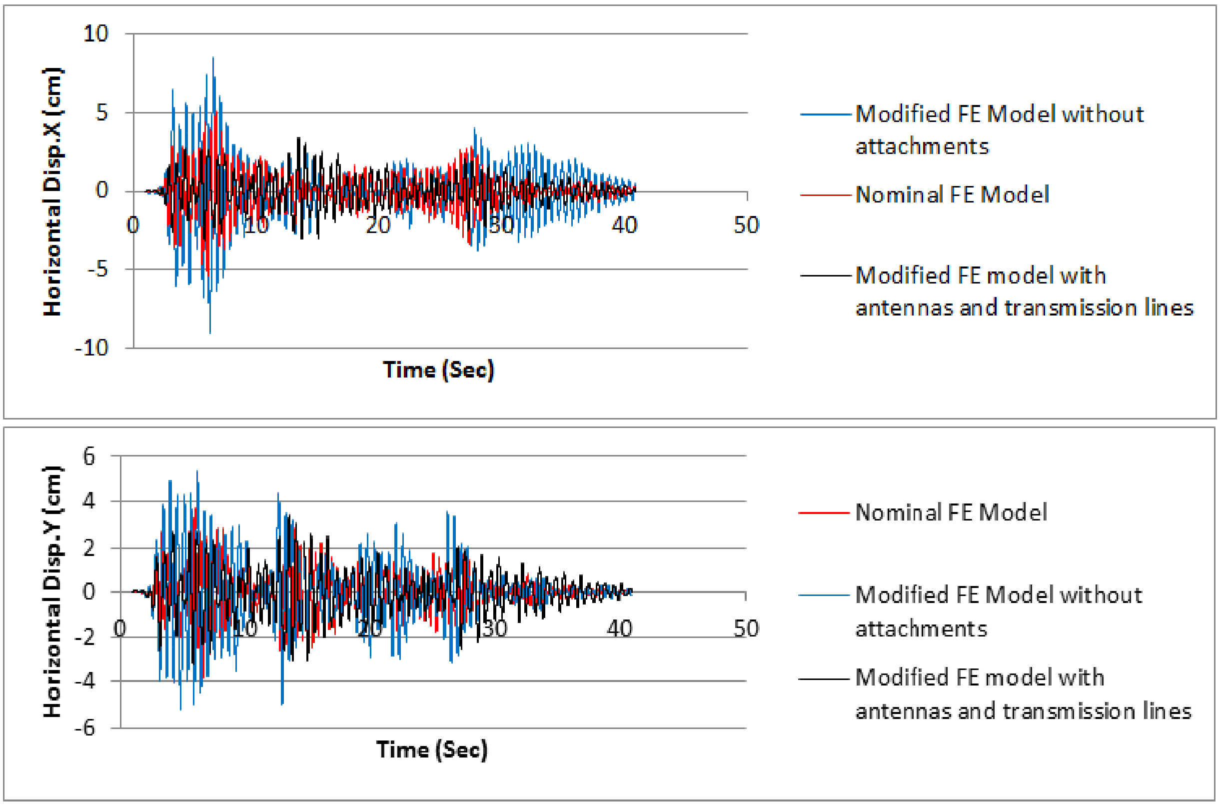


Figure3.2. Horizontal displacements of the mast at cable cluster elevation #1 (top cluster) along the X (along input) and Y (transverse to input)

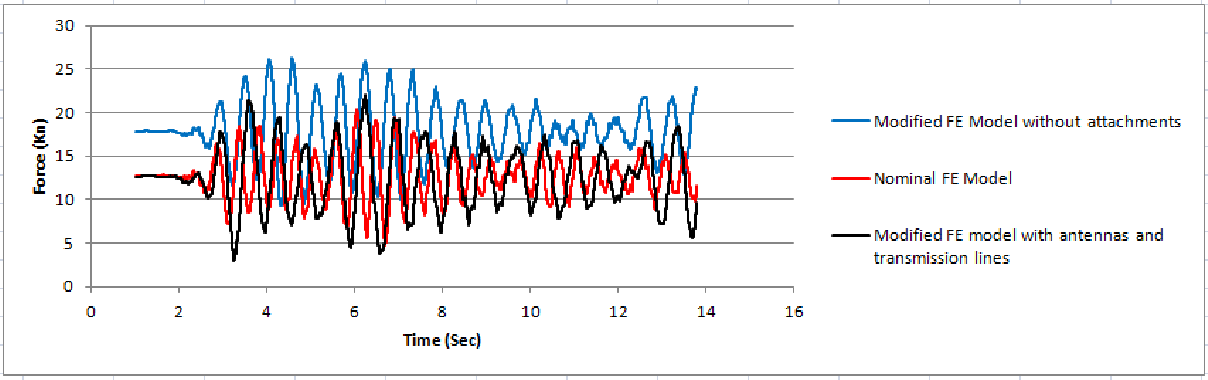


Figure3.3. Axial tension in a typical cable of Cluster #1 aligned with the input ground motion.

4. CONCLUSION

Ambient vibration tests on a guyed mast have provided valuable data for the validation of detailed finite element models used for nonlinear dynamic analysis. Fundamental frequencies of the cables are identified and average cable tensions are calculated on the basis of the extracted frequencies. Cable tensions are a very influent parameter on the mast natural frequencies. Also the study underlines the importance of the variability in cable tension on the seismic response of the structure. Predictive numerical models based on nominal parameters are deemed acceptable as long as a range of realistic tension values (within nominal tolerances) is considered. Frequency analysis of guyed masts including the uncertainty on the cable tensions will provide more realistic bounds of the structure's dominant natural frequencies and seismic response.

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