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PARAMETRIC STUDY OF THE BEHAVIOUR OF FIBRE-REINFORCED POLYMERS (FRP) STRUCTURAL POLES IN HIGH SEISMIC ZONES

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ABSTRACT

Structural poles carrying lighting fixtures and traffic signs as well as those supporting power and communication lines are traditionally made of timber, metals and steel-reinforced concrete. However, corrosion and aging problems deteriorate their structural integrity and architectural appearance. Recently, the tubes made of Fibre Reinforced Polymers (FRP) with their non-corrosive nature and high strength to weight ratio have been a favourable option for structural poles. Yet, the background about their structural behaviour, in general, and their performance under seismic conditions, in particular, is quite limited. Therefore, the present paper throws the light on a study that investigates the dynamic behaviour and seismic response of Glass GFRP structural poles in high seismic zones. Various parameters have been considered such as the height of the pole mast, the length of the pole arm and the weight of the pole fixture(s). The influence of these parameters on the pole dynamic characteristics as well as on the seismic straining actions induced at the pole base has been investigated. Further, the study results present an approach towards optimising the design of FRP structural poles subject to severe earthquake condition.

KEYWORDS

FRP, FEM, structural poles, seismic, parametric study, dynamic analysis.

INTRODUCTION

Structural poles all over the world have been manufactured for decades mainly of timber, metals (steel/aluminum) and (reinforced/pre-stressed) concrete. Recently, the superior characteristics of FRP such as their non-corrosive nature, high tensile strength and low mass density present FRP poles as potential replacement to conventional poles. Such potential is quite valid in locations where harsh weather and/or high seismic activities deemed responsible for the collapse of structural poles due to fatigue initiated by corrosion (Conner et al. 2005; Dexter 2002). Currently, hollow tapered Glass FRP (GFRP) tubes are widely produced and used as structural poles serving many engineering/construction sectors, e.g. lighting, communications and power lines, (NCN 2007; MFGC 2014). The low production cost of GFRP, compared to other types of FRP such as Carbon FRP (CFRP), while reasonably accommodating both serviceability and strength requirements qualify GFRP as an optimum FRP option for structural poles in high seismic zones. However, most of the recent standards and research programs related to FRP poles are dedicated to strength, fatigue and crash issues (Metiche and Masmoudi 2013; AASHTO-LTS 2009; Chien and Jang 2008; Elmarakbi and Sennah 2005). Therefore, this paper is a continuation of the author's research work in the area of dynamic/seismic analysis of structures, in general, (Salib 2012) and of structural poles, in particular (Salib and Abdel-Sayed 2012). Earlier, the dynamic behaviour and seismic response of structural poles made of concrete, steel, GFRP and CFRP were addressed for poles installed on footings and bridge decks (Salib and Abdel-Sayed 2012). That study concluded that FRP structural poles possess favourable dynamic characteristics due to their unique combination of light weight and mechanical properties. Herein, this study focuses on GFRP structural poles and the influence of various parameters on their dynamic behaviour and straining actions under seismic events. Among the investigated parameters are the height of the pole mast, the length of the pole arm and the weight of the pole fixture(s). A Time History (TH) analysis has been performed through a three Dimensional-Finite Element Modelling (3D-FEM) of the investigated poles. It is believed that the obtained results provide guidelines for an optimum design of GFRP structural poles in high seismic zones.

POLES DESCRIPTION AND INVESTIGATED PARAMETERS

The material properties and cross section dimensions of the investigated poles have been selected based on various GFRP poles available in the market, fabrication methods and related standards (NCN 2007; MFGC 2014; AASHTO-LTS 2009). Since a structural pole, in general, represents a free-standing member that is fixed at the ground level (i.e. vertical cantilever), maximum straining actions are induced at the mast base and decrease towards its tip. Therefore, most of the currently manufactured GFRP pole masts have tapered hollow profile with circular cross section as an optimum utilization of the mast material. The common production method for GFRP structural poles has been filament winding. The method provides flexibility in the cross section dimensions along the pole mast and arm thus optimising the pole weight and both material and fabrication costs. Further, this method allows orienting the fibres in various directions which optimises the material to be mostly utilized in its superior longitudinal direction under the different types of the induced straining actions. Herein, the proposed GFRP mast thickness and base outside diameter depend on the pole height, as listed in Table 1, while the mast tip has a fixed outside diameter of 80mm. Similarly, the GFRP pole arm has outside diameter at the face of mast based on the arm length (Table 2). Also, the pole arm has a fixed outside diameter of 80mm at the arm tip and a uniform 6mm thickness throughout its length. The material properties of the investigated poles are listed in Table 3.

Table 1. The mast dimensions of the investigated poles

Pole height (m)	6.0	9.0	12.0
Outside diameter of mast base (mm)	200	260	320
Mast thickness (mm)	6	6 (top 6.0m) 9 (bottom 3.0m)	6 (top 6.0m) 9 (between 6.0 & 3.0m) 12 (bottom 3.0m)

Table 2. The arm dimensions of the investigated poles

Arm length (m)	1.0	2.0	3.0
Outside diameter at mast face (mm)	100	120	140

Table 3. The material properties of the investigated poles

Tensile Modulus of Elasticity (MPa)	Specific Weight (kN/m3)	Tensile Strength (MPa)	Compressive Strength (MPa)
30000	17.0	400	200

The selected pole heights, H, represent a common range of standard poles. Most of the safety manuals and design guidelines for structural poles and traffic sign supports (SSM-Ontario 2011; OMUTCD 2012) require a minimum vertical clearance of approximately 5.50m to the underside of the roads/highways overhead fixtures. Thus, the minimum pole height investigated of 6.00m usually accommodates such requirement. Two other pole heights, 9.00m and 12.00m, are also studied to cover relatively higher poles. For poles carrying lighting fixture(s) and/or traffic signs that intended to be located within the overhead zone of the traffic lanes, the pole arm usually stretches for few meters. While for other light poles and communication/power poles, the pole fixture(s) are relatively concentric with the pole base. Therefore, the length of the investigated pole arm, L, covers a range between 1.00m and 4.50m. The selected fixture mass values, m, (25.0 kg, 50.0 kg, 75.0 kg and 100.0 kg) cover wide range of common lighting fixtures and traffic signs (Figure 1a).

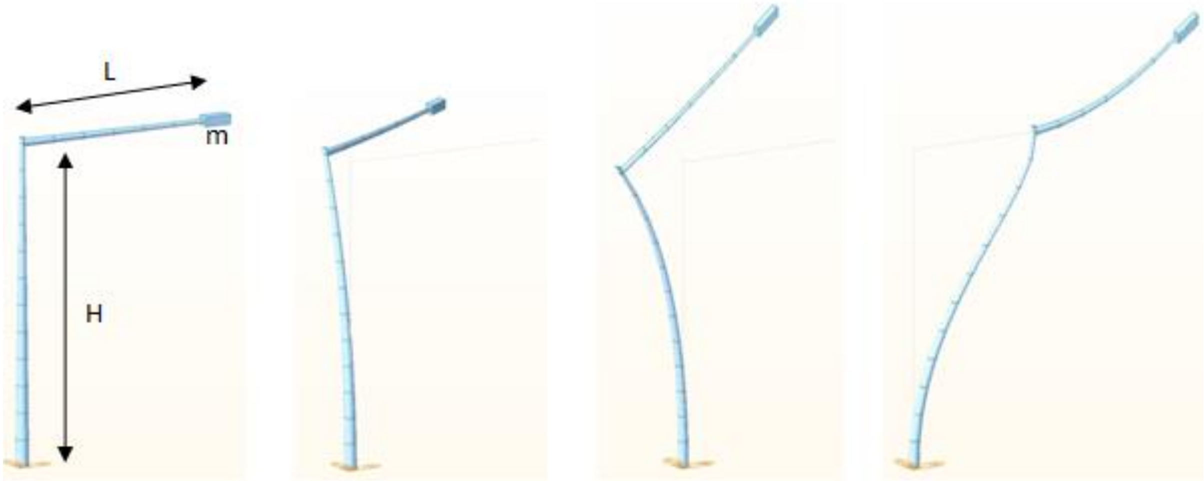
FINITE ELEMENT ANALYSIS (FEA)

Modelling

A 3D-FEM of the investigated poles has been developed. The pole mast and arm have been modeled as beam elements. A fully fixed support (deformations are restricted in the 6 degrees of freedom) is introduced at the mast base. The fixture(s) mass is applied at the tip of the pole arm (Figure 1a).

Dynamic Analysis

A major step towards understanding the dynamic characteristics of structures, in general, and those located in seismic zone, in particular, is through their fundamental Modes Of Vibration (MOV). A modal analysis has been performed through the developed FEM. Figure 1 shows the first, second and third MOV of the pole FEM with 6m mast height, 100kg fixture mass and 3m arm length. Herein, the first MOV, representing the minimum natural frequency, f, introduced by the system, is considered a major dynamic characteristic of the poles.



(a) FEM (b) 1st MOV; f=0.478 (c) 2nd MOV; f=0.538 (d) 3rd MOV; f=1.379

Figure 1. Isometric view of FEM and MOVs for the pole with H=6m, L=3m and m=100kg.

Seismic Analysis

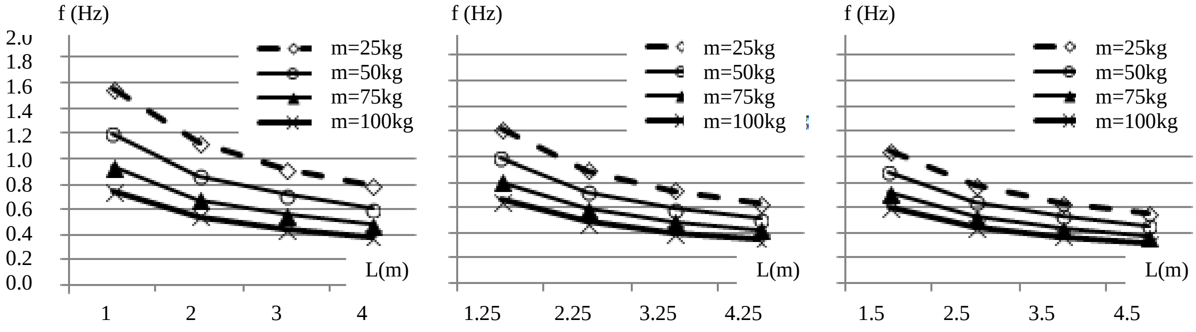
The details of the seismic data of the proposed study site were provided in a previous study where the magnitude of the applied earthquake acceleorgram approaches ± 0.8g (Salib and Abdel-sayed 2012). Due to the unsymmetrical mass and geometry of the poles, the seismic event has been applied in each horizontal direction (X and Y) separately. For a statically determined structure such as the subject inverted L-shape cantilever, the maximum bending moment induced at the fixed support (mast base) is considered a major straining action induced in the pole assembly.

RESULTS AND DISCUSSIONS

The frequency obtained of the first MOV for the entire range of the investigated parameters are illustrated in Figure 2. It can be seen that the first MOV frequency of the poles is inversely proportional to both the height of the pole mast and the length of the pole arm (major part of the system flexibility) as well as the fixture mass (major part of the system mass). Such behaviour reflects a basic principle of structural dynamics as the system that possesses higher stiffness and less mass vibrates at higher frequency through the following relationship (Tedesco et al. 1999):

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \quad (1)$$

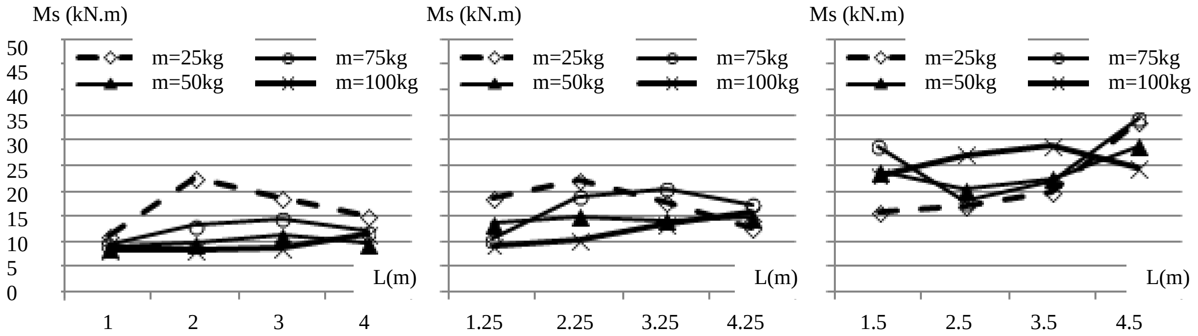
Where f = vibration frequency; k = system stiffness; and m = system mass



(a) H=6m (b) H=9m (c) H=12m

Figure 2. Natural frequency of the 1st MOV, f, of the investigated poles.

The values of the seismic bending moment at the mast base, Ms, obtained under the different parameters investigated for the subject poles are illustrated in Figure 3.



(a) H=6m (b) H=9m (c) H=12m

Figure 3. Maximum seismic bending moment at mast base, Ms, of the investigated poles.

Figure 3 shows that, in general, the magnitude of seismic straining actions is proportional to the mast height. For relatively high masts, e.g. H=12m (Figure 3c), the maximum Ms takes place at the extreme of the investigated values of both arm length, L, and fixture mass, m. On the other hand, for shorter masts, e.g. H=6m and 9m (Figure 3a and 3b), the maximum Ms takes place at shorter arm length (L=2m and 2.25m, respectively) and at the smallest fixture mass (m=25kg). Part of the interpretation to such behaviour can be found in the dynamic characteristics of the investigated poles presented by the frequency of the first MOV. The stiffer (e.g. less arm length) and lighter (e.g. less fixture mass) pole has higher frequency, i.e. experiences higher acceleration during the seismic event and consequently develops higher straining actions (Salib and Abdel-Sayed 2012). Further, increasing the fixture mass at the tip of the pole arm changes the MOVs and their associated Modal Participation Mass (MPM) which can be in favour of reducing the seismic straining actions. This dynamic characteristic has been widely used recently as a passive to semi-active damping method of both existing and new structures in high seismic zones through the so called Tuned Mass Dampers (TMD) (Constantinou et al. 1998).

As a step towards developing design guidelines for GFRP structural poles, the results shown in Figures 3a to 3c are combined in Figure 4 through a presentation of the normalized values of the investigated parameters and obtained bending moments. The ratio between Ms and the bending moment induced at the same section (mast base) due to the permanent dead loads (including the fixture mass), Md, is plotted against the ratio L/H for different fixture mass, m. Herein, Ms/Md, L/H and m is considered an index to the severity of the seismic event, an index to the flexibility of the pole assembly and an index to the mass damping effect, respectively.

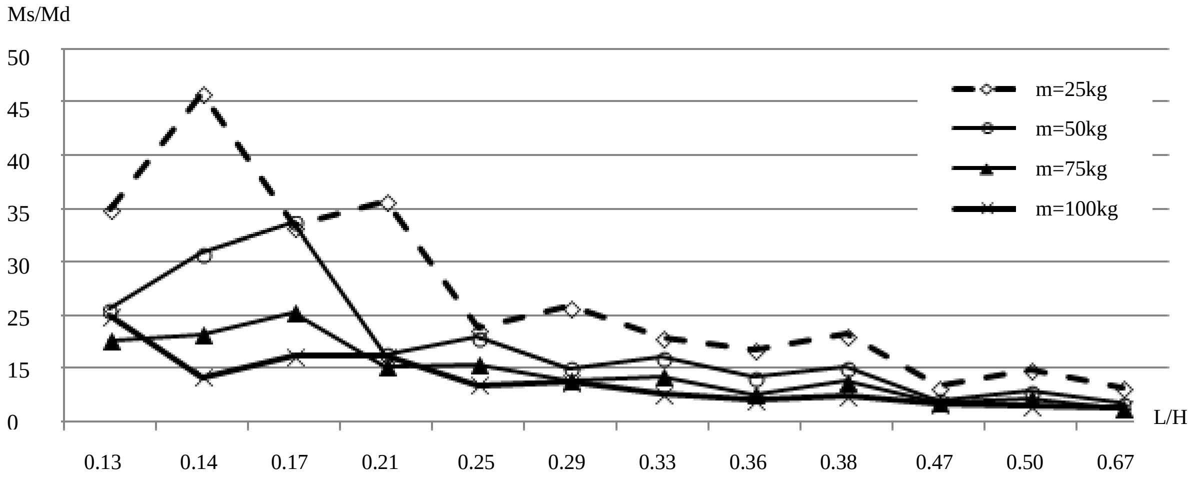


Figure 4. The obtained ratio Ms/Md vs. L/H of the investigated poles.

Although the curves are slightly rough, the trend of results can be noticed. The value Ms/Md decreases significantly with the increase of L/H and m. The results emphasize the dramatic difference between the static and dynamic behaviour, especially in high seismic zones. While increasing the fixture mass and the pole arm length is directly proportional to the magnitude of the static bending moment at the mast base, the seismic bending moment at the same location can be considerably reduced. In other words, considering the expected maximum fixture mass and maximum pole arm length as a traditional approach for structural poles design may not be conservative at all for poles located in high seismic zones.

CONCLUSIONS

An analytical study has been performed on GFRP structural poles in order to investigate the influence of parameters such as the pole dimensions and supported mass on the pole dynamic behaviour and seismic response. Based on the obtained results, the following can be concluded:
The major dynamic characteristics of the poles, presented by the first fundamental MOV frequency, show that the frequency is inversely proportional to both the height of the pole mast and the length of the pole arm (major part of the system flexibility) as well as the fixture mass (major part of the system mass);

The response of the investigated poles to severe seismic events demonstrates a strong relationship between the first MOV and the magnitude of seismic straining actions, presented by the seismic bending moment at the mast base;

The ratio of the seismic to static permanent moment at the mast base is inversely proportional to the fixture mass and the ratio of the arm length to the mast height; and
The conventional approach for structural poles (equivalent static) seismic design based on maximum fixture mass and maximum pole arm length can significantly under-design the poles located in high seismic zones; and

A smart pole design can accommodate the traffic requirements and support various fixtures while optimising the pole material, fabrication and construction cost and, further, improving its seismic performance.

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