Developing Fragility Curves for Seismic Vulnerability Assessment of Tubular Steel Power Transmission Tower Based on Incremental Dynamic Analysis

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SUMMARY:
According to the experience on vulnerability of power networks in past earthquakes, it has been learned that the continuous operation of power network, especially power transmission towers, can help better emergency response and relief operations. Regarding to durability and ease of manufacturing and installation, many utilities in recent years, prefer to use the tubular steel towers rather than over lattice steel for new power lines and tower replacements. This study focuses on developing fragility curves of tubular steel power transmission towers. The main goal of this research is to assess the seismic performance reliability of tubular steel power transmission towers subjected to earthquake loadings by probabilistic approach. Fragility functions ,which provide the probability of exceeding a prescribed level of damage for a wide range of ground motion intensities, are the major requirements for seismic loss estimation and are widely used in the seismic risk management and related studies. In fragility curves, structural demand and ground motion intensity measure are two key parameters for determining exceedance probability of predefined performance level. In this research, displacement and spectral acceleration have been selected as structural demand and ground motion intensity measure, respectively. Due to lack of knowledge about defining structural limit states for tubular steel towers, nonlinear static pushover analysis has been conducted and then by corporation analysis results with engineering judgment, performance levels have been chosen. Seven far-source earthquakes, in the 0.2-0.8g PGA range, have been selected for conducting nonlinear dynamic analysis. It is notable that selected records are compatible with site specifications. By performing incremental dynamic analysis (IDA) for each ground motion record, fragility curves have been developed. Finally, the results have been discussed by interpreting the fragility curves.

Keywords: Fragility Curves, Risk Management, Power Transmission Tower, Incremental Dynamics Analysis, Nonlinear static pushover analysis

1. INTRODUCTIONS

The electric lines that generate the most public interest are high-voltage transmission lines. These are the largest and most visible electric lines. Most large cities require several transmission lines for reliable electric services. The amount of electric power in each line, at any given moment, depends on generation production and dispatch, Customer use, the status of other transmission lines and their associated equipments and even the weather. Earthquake causes extensive direct and indirect losses in which the damages to lifelines play an important role. Power network and its sensitive components are key elements among all other groups of lifelines such as telecommunication and transportation networks, pipelines, etc. It has been learned from the past earthquakes that the existence of power network, especially transmission towers, can facilitate the rescue and relief operations and lead to more saving lives [Sadeghi et all 2010]. According to the experience on vulnerability of power networks in past earthquakes, it has been learned that the continuous operation of power network, especially power transmission towers, can help better emergency response and relief operations. Regarding to durability and ease of manufacturing and installation, many utilities in recent years, prefer to use the tubular steel towers rather than over lattice steel for new power lines and tower replacements. This study focuses on developing fragility curves of tubular steel power transmission towers based on probabilistic approach. Several researchers have studied the effects of earthquake on transmission towers. Ghobarah, Aziz, and El-Attar (1996), Li, Shi, and Jia(2003), Li, Shi, Wang, and Jia(2005),Li Tian, Hongnan Li, and Gouhuan Liu (2010) have studied the effect of earthquake loading on transmission towers. Yin, Li, Liu, and Zhai (2005), (2005) have studies seismic damages on power transmission towers; but none of these mentioned researches have any risk management horizon as a part of urban lifelines. This paper tries to use a probabilistic approach to use on past earthquakes risk management by developing fragility functions.

1. POWER TRANSMISSION TOWER

Transmission lines are larger than common distribution lines that exist along rural roads and city streets. Transmission line poles or structures are between 18 to 42 meters tall. Common 63Kv Distribution line structures are approximately 20 meters tall. The transmission tower is an important accessory and performance of the transmission line that depends very much on the design of the transmission tower. The electric transmission towers or pylons can be classified several ways. The most obvious and visible tower types are:

- Tubular steel tower
- Waist-type tower
- Double-circuit tower
- Guyed-V tower
- Guyed cross-rope suspension tower
- Crossings tower

1.1. Tubular steel tower

In many cases due to public resentment, the use of lattice structures has been restricted. Some power companies for high and extra high-tension transmission lines have used steel tubular pole structures quite successfully. The installation of these structures is costly but requires less time. The tubular structure can be a single tubular form or H-form. It can be designed for carrying two or more circuits. More transmission companies have started using of this type of tower especially in populated areas.

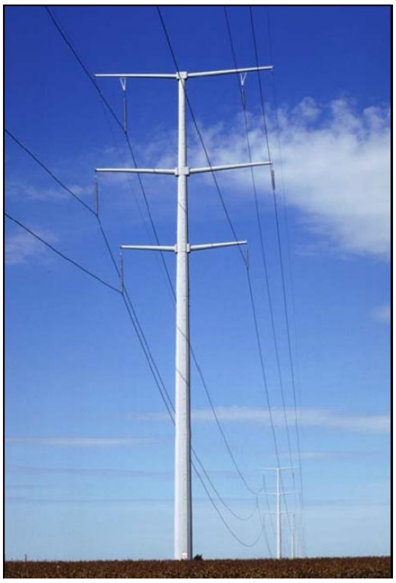


Figure 1. Tubular power transmission tower

The use of Tubular steel tower shape, height and sturdiness (mechanical strength) depend on the stresses to which they are exposed. In some areas where single-pole structures are preferred, weak or wet soils may require concrete foundations for support. A tubular power transmission tower consists of multiple parts, most of which owned by different companies. Regularly this tower consists of the following parts: Body, Arms, and Insulators.

2. AN OVERVIEW ON DEFINITION OF FRAGILITY FUNCTION AND ESTIMATION METHOD

Due to practical reasons, continuous damage in structures is divided into several discrete damage states [Porter 2000]. Fragility function estimates the conditional exceeding probability of damage from a damage state at given ground motion intensity:

$$F_i(im) = P(D > d_i \mid IM = im) \tag{2.1}$$

Where, F_i (im) is the probability of exceeding damage "D" from damage state "d_i" at given ground motion "IM=im". Ground motion intensity parameters denote the magnitude of ground motion, which is measured by Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV) or Spectral Displacement (SD). Damage state "i" is defined by non-damage state (i=0) to the n^{th} damage state (i=n) by qualitative and analytical definitions [HAZUS 1999] .Since damage in structures, in this study, is measured by Damage Index (DI), Equation1 is changed to:

$$F_i(im) = P(DI > di_t \mid IM = im) \tag{2.2}$$

Where, di_t is the damage index at the threshold of damage states. By Having the Probability Density function (PDF) of "DI" or its cumulative distribution function (CDF) at every "im" (fim (di) and (t) F_{im} (dit)), Eqn 2.2 is evaluated from probabilistic theorem:

$$F_i(im) = P(DI > di_t \mid IM = im) = 1 - F_{im}(di_t) = 1 - \int_{-\infty}^{di_t} f_{im}(di)d(di) \tag{2.3}$$

In this paper, PDF of DI is evaluated by multi-stripe analysis [Aslani and Miranda 2004 and Jalayer 2003]. Here, transmission tower is analyzed subjected to several ground motion records that are scaled to specific IM (here PGA) level and distribution of structural response in the particular IM (for structural case) is estimated from the results of the nonlinear analysis set. Based on these assumptions, procedure of fragility curve development for real structure(s) is summarized in three major steps shown in flowchart of methodology given in Figure 2[Nasserasadi et all 2009].

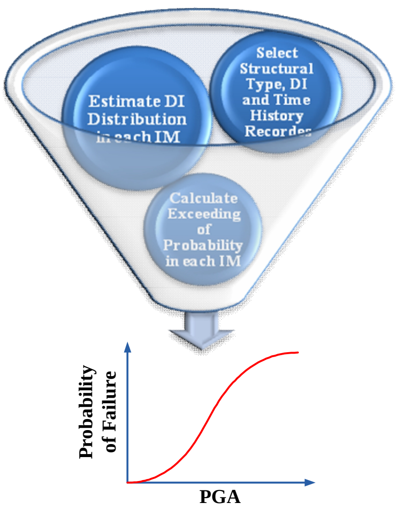


Figure 2. Developing Fragility curve procedure [Nasserasadi et all 2009].

3. STATEMENT OF THE PROBLEM

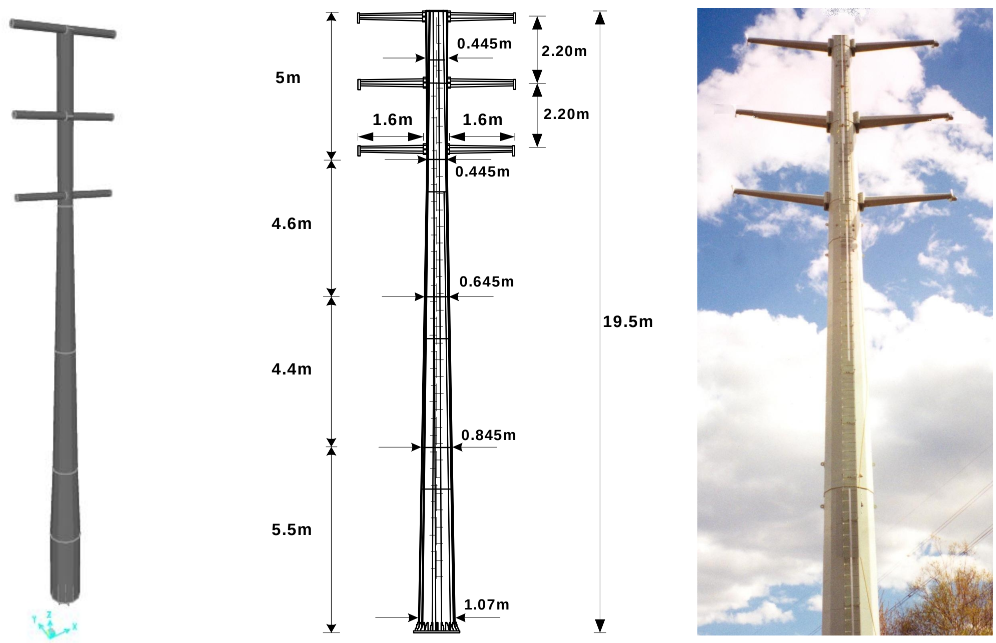
In this section, case study tubular tower 19.5m height, which is common for 63Kv transmission lines, has been discussed. It is apparent that these transmission towers play vital role to have continues electricity after an earthquake. The analyses are performed by advanced finite element software; for investigating structural performance, Maximum Base shear is derived. This is an important structural parameter, which can describe the sustainability of the tower. Finally, with a set of data, fragility curves are developed and discussed.

3.1. Structural modelling

Refer to the technical documents, material of tower members is ST-37 and ST-52 steel grade with yielding stress F_y=2400 Kg/cm² and F_y=3600 Kg/cm² respectively. Modulus of elasticity is E=2100000 Kg/cm² and passion ratio equals to ν=0.3. According to structural details, fixed support is assigned in base and arms modeling. The design of transmission tower and line is complex and needs to consider loading under different conditions. Specification of this tower is illustrated in Table1.

Table 1. Tubular Tower (19.5m) Detailing

Parts	Height(mm)	Initial Width(mm)	End Width(mm)	Steel Grade
1st	5500	1070	845	ST-52
2nd	4400	845	645	ST-52
3rd	4600	645	445	ST-37
4th	5000	445	445	ST-37



(a) (b) (c)

Figure 3. Software modeling (a), Structural detail (b) and real monopole tower(c).

Pole height and load capacity limitations, control allowable span length either on the basis of ground clearance or ability to support heavy wind and ice loads. High Wind, Heavy Ice and Normal Wind-Ice are three loading cases, which are used for analysis. Regarding to Iranian guideline No.402 for designing the power transmission lines, heavy ice is selected as critical load case. Two condition are considered for this case; balance loading (forces are applied two side of the tower) and unbalance loading (forces are applied one side of the tower). Therefore, 2096.4 Kg vertical and 204.1 Kg Horizontal force are applied on each tower's arms (see Table 2). Theses loading are calculated for 63Kv Distribution line with length of 19 Km and design span equals to 250 meter. Maximum transmission power is 20 Mega Watts. Insulator type is U120B and maximum ice thickness is 20mm.

Table 2. Heavy Ice Loading Details.

Load Direction	Balance Force(Kg)	Unbalance Force(Kg)
Horizontal	2096.4	1480.6
Vertical	204.1	102.1

3.2. Seismic input

Seven earthquake records are selected to be employed as the tower base excitations. All the records normalized to their maximum ground acceleration as series of (0.1g, 0.2g, 0.3g, 0.35g, 0.45g, 0.5g, 0.6g, 0.7g, 0.8g, 0.9g, 1g and 2g) and all of them would be baseline corrected. PGA has been selected as intensity measure criteria on developing fragility curve [Vamvatsikos and Cornell 2002]. Selected records along with their characteristics are describing on Table 3:

Table 3. Earthquake Details

Earthquake	PGA(g)	Location	Moment Magnitude	Year
Tabas	0.85	Iran	7.8	1978
Bam	0.81	Iran	6.5	2003
Naghan	0.73	Iran	5.9	1977
Elcentro	0.3	USA	7.1	1940
Kobe	0.5	Japan	6.9	1995
Cape Mendocino	0.8	USA	7.1	1992
Hollister	0.38	USA	5.9	1989

3.3. Frequency Analysis

Frequency analysis has been performed to derive transitional mode shapes and frequencies. As a summery, it's obvious that this structure categorized as a low frequency structure. Frequencies are illustrated in Table 4.

Table 4. Frequency Analysis Result

Mode	Frequency(Hz)	Period(Sec)
1st	0.6569	1.5159
2nd	0.6737	1.4843
3rd	3.5971	0.2780

3.4. Analysis Method

Nonlinear dynamic approach has been performed for tower analysis. For this purpose, acceleration time history records are imported to the software. Totally 84 analysis are performed. Maximum Base shear of the tower is derived. Damping ratio is assumed 5%[Vamvatsikos and Cornell 2002].

4. DEFINITION OF LIMIT STATES

The authors didn't access any predefined structural limit state of damage index for this special structure, therefore they performed a nonlinear static pushover analysis with a uniform pattern loading along the tower height and the base shear related to the first plastic hinge is selected as limit state (see Figure 4).

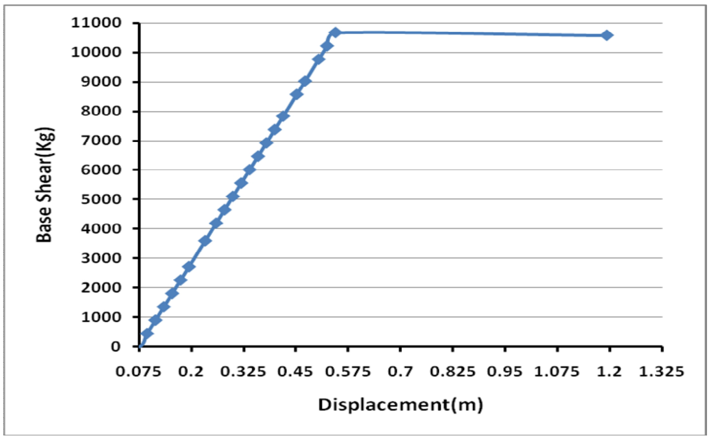


Figure 4. Pushover Curve of tower

5. DEVELOPING FRAGILITY CURVES AND NUMERICAL RESULTS

The distribution of maximum Base shears, estimated from the analyses, is shown in Figure 5. The solid line represents the mean value of the results. Lognormal distribution was better fitted than normal distribution to results in general.

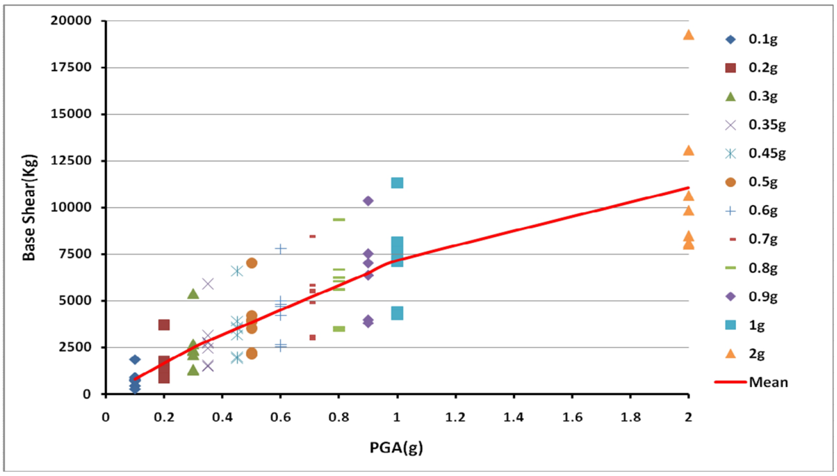


Figure 5. Maximum base shear of tower in each PGA levels

The fragility value at each PGA (F_i (PGA)) is estimated by changing the notation of Equation 3 and replacing the distribution of damage index ($f_{im}(di)$) by lognormal distribution of ISD $(f(isd) = \varphi\left[\ln(ISD), \beta_{sd}\right]$:

$$\begin{aligned} F_i(sd) &= P(D > d_i \mid SD = sd) = 1 - P(D \le d_i \mid SD = sd) \Rightarrow \\ &= 1 - \Phi(1/\beta_{sd} . \ln(ISD_i / I\hat{S}D_{sd})) \end{aligned} \tag{5.1}$$

Where, ISD_i is the mean ISD (result) threshold of damage states. Fragility curve shown in the Figure 6 are estimated by fitting a lognormal cumulative distribution function:

$$F_i(sd) = P(D > d_i \mid SD = sd) = \Phi\left(\frac{1}{\beta_i} \ln\left(\frac{sd}{SD_i}\right)\right) \tag{5.2}$$

Where SD_i and β_i are mean and deviation of the function respectively [K Nasserasadi et all 2009].

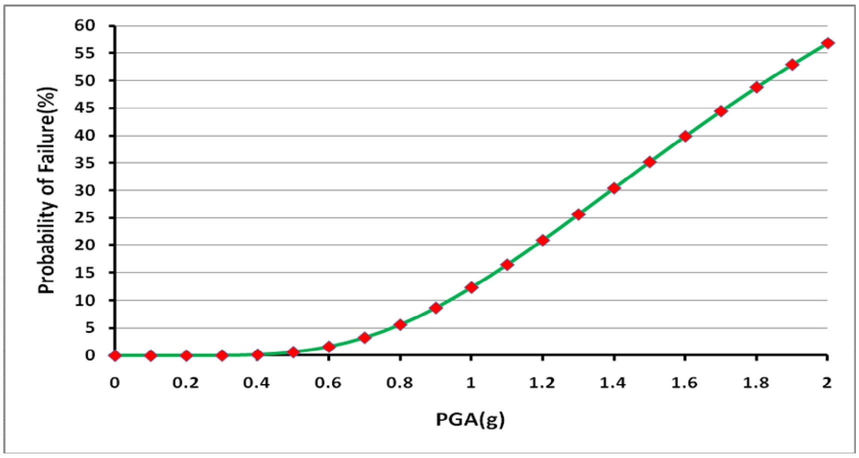


Figure 6. Fragility curve for structural performance of tower

By reviewing the results, this condition could be predictable, because none of the results was on structural limit state range.

6. CONCLUSIONS AND PROPOSALS FOR FUTURE WORK

By studying fragility curves witch presented on Figure 6, the following conclusions could be stated:

1. At the acceleration more than 1.0g, the probability of structural fragility at the peredefined damage level has exceeded more than 10 percent.
2. The general conclusion about the structural performance of this system is that it has high reliability even at very high peak ground accelerations.

The authors propose future works conduct on some additional field, for example: considering the effect of tower's underlying soil and soil structure interaction (SSI), deriving better intensity measure for fragility curve such as S_a, studying the behavior of nonstructural equipment of power transmission networks, dynamic interaction of cable on structure….

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