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SEISMIC FRAGILITY OF TRANSMISSION TOWERS IN KOREA

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ABSTRACT: Seismic fragility curves of transmission towers in South Korea are developed. Linear elastic finite element models of the transmission towers are developed for a series of time history analyses. For a set of 20 recorded ground motions are used to develop fragility curves. Limit states are defined in terms of the yielding and buckling of the structural members. It is concluded that the transmission towers are safe under the design level earthquake in South Korea. For 756 kV and 345 kV transmission towers, the buckling is more likely to happen before the yielding of the member occurs, while the opposite is observed for the 154 kV transmission tower. A nonlinear analysis considering soil-structure interaction will be required for a more accurate assessment of the seismic performance of the transmission towers.

1. Introduction

A damaging earthquake is unpredictable and tends to affect a large area. A strong earthquake causes a severe damage to buildings and lifelines in urban areas, in particular. A highly industrialized country such as South Korea has high risk to earthquake disaster due to its high population density. In South Korea, 80 % of the population is concentrated in urban areas, which are more vulnerable to an earthquake. Direct earthquake damage to lifeline structures also causes secondary effects such as the disruption of the power, gas, or water. In many cases, the secondary effect causes more socio-economic loss than a direct structural damage.

To achieve high efficiency to meet the high electricity demand of urban area, the power transmission commonly uses high voltage. The power transmission type in South Korea changes from 66 kV and 154 kV in the past to 345 kV in the 1970's and 765 kV in the 1990's. Accordingly, the transmission tower gets taller and larger as the transmission voltage gets higher. In designing the power transmission tower, the wind load is considered as the governing lateral load that overrides the earthquake load because transmission towers are basically very light structures. For example, the National Electric Safety Code (2012), ASCE Guideline (2009) in the United States and the transmission tower design standard in South Korea (2010) require considering the wind effect rather than the earthquake effect. Therefore, the cross sections of the structural members are determined by the combination of the self-weight of the tower, tensions of the transmission wires, and the wind load. However, we have observed that transmission towers are vulnerable to strong earthquakes. 1976 Tangshan earthquake in China, 1989 Loma Prieta earthquake in USA, 1995 Kobe earthquake in Japan, 1999 Chichi earthquake in Taiwan, and 2008 Sichuan earthquake in China all damaged transmission towers and, consequently, caused power outage (Liu and Tang 2012). Therefore, it is necessary to understand the seismic vulnerability of transmission towers to establish a proper earthquake disaster management.

A limited number of literatures are found on the seismic behavior of transmission towers. Moon et al. (2009) studied the seismic behavior of a specific connection of structural members of the transmission tower by experimental method. A few studies evaluated the seismic damage of transmission towers based on the finite element method (Yin et al. 2000, Li et al. 2005, Liu and Tang 2012, Wang et al. 2014).

McClure and Lapointe (2003) used a general-purpose program to develop a modeling method for the transmission tower considering the effect of the transmission cable. Li et al. (2005) studied the behavior of the transmission tower and cable system using a simplified analytical model and an experimental method. Tian et al. (2010) investigated the effect of the connection types of the transmission cables, and the direction and the spatial variability of the earthquake on the geometric behavior of transmission towers.

In this study, we investigated the seismic behavior of the transmission tower in South Korea and developed seismic fragility curves to provide information about predicting earthquake damage to transmission towers. Four representative types of transmission towers are selected for computational analyses where detailed 3-dimensional finite element models are developed. A set of historic ground motions are selected for incremental dynamic analyses. The yielding in tension and the elastic buckling of structural members are considered as the limit states when developing seismic fragility functions. Seismic fragility functions are derived using the maximum likelihood estimation method (Shinozuka et al. 2000).

2. Modeling of Transmission Tower

The transmission tower supports power cables that run from the power plant to substations and distribution stations. Typical types of transmission towers constructed in South Korea are presented in Table 1 (KEPCO 2010). They are categorized by the transmission voltage of electricity. Two types of cross sections are available for the structural member of transmission towers, i.e. the angle-type and the pipe-type cross sections. Figs. 1(a) and 1(b) show the photos of transmission towers with the pipe-type members and the angle-type members, respectively.

Table 1 – Typical types of transmission towers in South Korea (KEPCO 2010).

Category	Features
765kV	Transmission of large-scale residence complex and large demand area
345kV	Interregional main line and large-scale supply chain of the downtown area
154kV	Distribution lines in 345kV area

(a) Pipe-type transmission tower

(b) Angle-type transmission tower

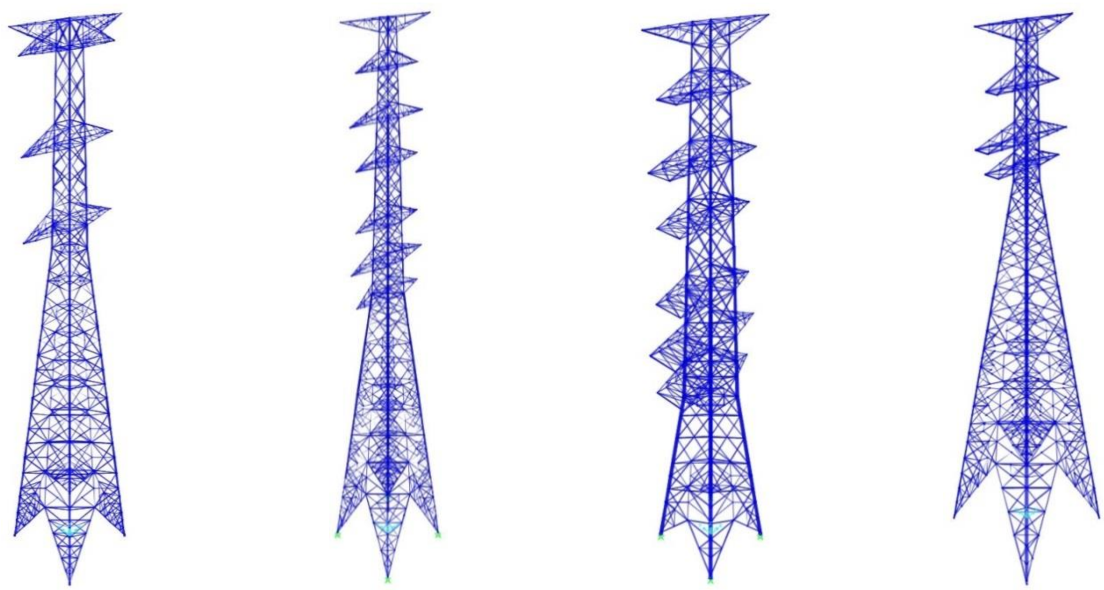
Fig. 1 – Photos of transmission towers: (a) pipe-type and (b) angle-type.

In this study, both of the pipe-type and the angle type 345 kV transmission towers are selected for the analytical study. Pipe-type 756 kV and 154 kV transmission towers are also selected for this study to compare different seismic responses of transmission towers with different sizes. Properties of the transmission towers used in this study are presented in Table 2.

Table 2 – Properties of various transmission towers selected for this study.

Category	Dimension		Cable load		
	Height (m)	Width (m)	Unit weight (kgf/m)	Span length (m)	Number of strung wore
765kV pipe type	155.5	26.7	1.836	500	4
345kV angle type	122.8	19.8	1.637	450	4
345kV pipe type	88.6	13.4	1.637	450	4
154kV angle type	62	14.5	1.637	400	4

Finite element models of the transmission towers are developed within the capability of SAP2000, general purpose analysis software. Conventional beam-column and truss elements are used to model the main structural members and bracing members, respectively. The effect of the connected cables to the transmission tower is considered in the form of the equivalent static load to the transmission tower. Therefore, the tower-cable interaction is not considered in the seismic analysis. The hinge support condition is assumed for all four legs of the transmission tower and the soil-structure interaction is not considered. Fig. 2 shows the finite element models of the selected types of the transmission towers where the relative scale of different transmission towers are not considered.



(a) 756 kV (b) 345 kV, pipe-type (c) 345 kV, angle-type (d) 154 kV, angle type

Fig. 2 – Transmission tower models.

The seismic behavior of the transmission towers are evaluated using the time history analysis procedure. Twenty ground motion time histories are arbitrarily selected from the strong motion database provided by the Pacific Earthquake Engineering Research Center (2014). Twenty ground motions provide uncertainty in the ground motion profiles when developing the seismic fragility curves. Table 3 lists the magnitudes and PGAs of the selected set of ground motions.

Table 3 – Selected ground motions.

NO	Earthquake	Magnitude	Station	PGA direction	
				X(g)	Y(g)
1	Anza, USA	4.92	Pinyon Flat	0.079	0.131
2	R.V. Bishop, USA	6.19	Mcgee Creek Surface	0.044	0.124
3	Caldiran, Turkey	5.82	Station Code : 37	0.006	0.097
4	Chichi, Taiwan	5.28	CHY002	0.147	0.024
5	Coyote Lake, USA	7.21	Coyote LK Dam-San Martin	0.015	0.279
6	El-Centro, USA	6.33	El Centro array #1	0.079	0.134
7	Erzican, Turkey	6.60	Erzikan	0.487	0.205
8	Imperial Valley, USA	7.62	Aeropuerto Mexicali	0.327	0.243
9	Kobe, Japan	5.74	FUK	0.030	0.035
10	Loma Prieta, USA	5.99	Apeel 10 Skyline	0.087	0.067
11	Lytle Creek, USA	4.26	Castaic Old Ridge RT	0.003	0.026
12	MT.Lewis, USA	6.93	Halls Valley	0.134	0.098
13	New Zealand	5.33	Maraenui Primary School	0.033	0.025
14	Norcia, Italy	6.69	Bevagna	0.006	0.040
15	Northridge, USA	6.06	Slhambra-Premont School	0.101	0.055
16	Parkfield, USA	7.68	Cholame #12	0.011	0.063
17	Spitak, Armenia	5.90	Gukasian	0.157	0.167
18	Victoria, Mexico	6.53	Cerro Prieto	0.621	0.149
19	Whittier Narrows, USA	6.27	Alhambra Fremont	0.145	0.414
20	Yorba Linda, USA	6.90	Brookhurst & Crescent	0.009	0.009

Fig. 3 shows the response spectra of the selected ground motions where the orange line indicates their average response spectrum. It should be noted that the PGAs of all the ground motions are scaled to 0.2 g that is the design level acceleration in many design code in South Korea.

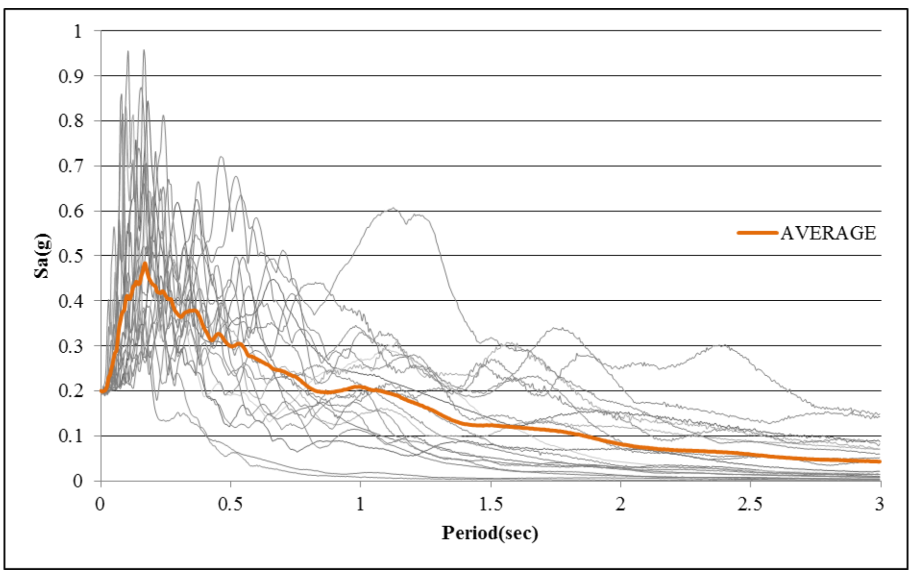
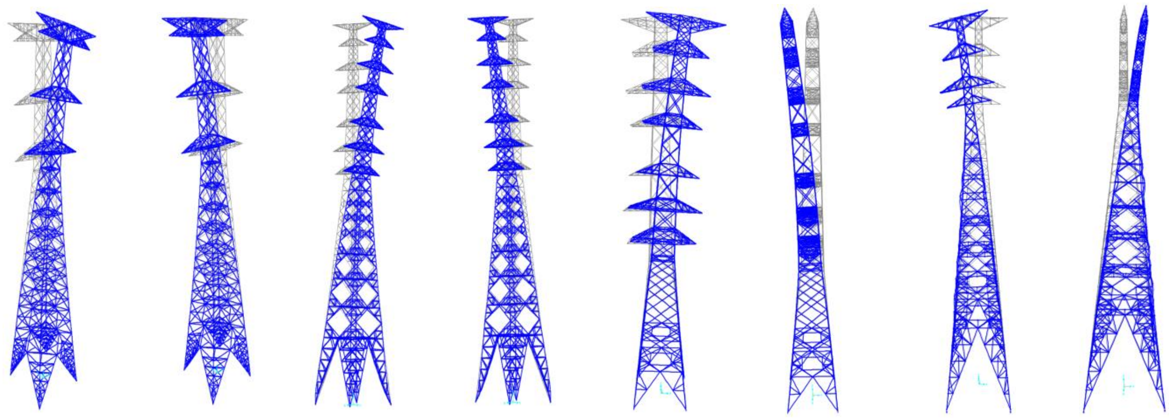


Fig. 3 – Acceleration response spectra of selected ground motions.

3. Time History Analysis Results

3.1. Interpretation of eigenvalue analysis

An eigenvalue analysis of the transmission tower is performed to understand its dynamic characteristics. The fundamental periods of various transmission towers range from 0.51 sec to 1.96 sec. Fig. 4 shows the first two mode shapes and the corresponding vibrational periods. The first two modes are the quarter sine curves in two plane directions as shown in Fig. 4 and the torsional mode follows.



mode1 mode2 mode1 mode2 mode1 mode2 mode1 mode2

T=1.96 T=1.95 T=1.46 T=1.46 T=0.66 T=0.65 T=0.51 T=0.51

a) 765kV pipe type b) 345kV angle type c) 345kV pipe type d) 154kV pipe type

Fig. 4 – Modes of vibration.

3.2. Time History Analysis Results

Linear elastic time history analyses are performed for each of the 20 ground motions. Different transmission tower models show different behavior characteristics. For 765 kV, 345 kV angle-type, and 345 pipe-type transmission towers, braces reach to the yielding capacity or buckling capacity before any damage to the main members occurs. On the other hand, 154 kV transmission tower experiences the yielding or buckling of the main member before the damage of the brace occurs. To consider a wide range of ground motion intensity in developing the fragility curve, each ground motion is scaled so that its PGA matches to a target PGA from 0.01 g to 5.0 g.

4. Seismic Fragility Analysis

4.1. Development of Seismic Fragility Functions

Seismic fragility curves of the transmission tower models are developed. Sample probability that exceeds the limit state for specified earthquake intensity is computed based on a set of 20 time history analyses where the PGA is used as the measure of earthquake intensity. Sample probabilities are computed for a range of PGAs, i.e. from 0.01 g to 5.0 g with 0.01 g interval. Empirical fragility curves are developed based on the sample probabilities where these curves are fitted by lognormal cumulative distribution functions (CDFs) according the maximum likelihood estimation procedure (Shinozuka *et al*. 2000). A lognormal CDF is expressed as

$$\mathrm{P} = \Phi\left(\frac{\ln PGA - \ln c}{\zeta}\right) \tag{1}$$

where $\Phi(\cdot)$ is the standard normal CDF, *c* is the median, and ζ is the standard deviation of the lognormal distribution. In this approach, *c* and ζ are determined by maximizing the likelihood function that is defined by

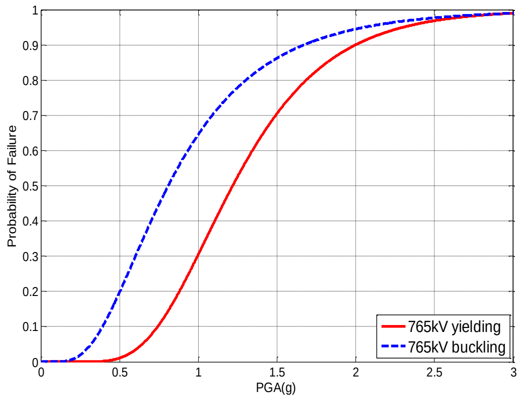
$$L = \prod_{i=1}^{N} [F(PGA)]^{x_i} [1 - F(PGA)]^{(1-x_i)} \tag{2}$$

where *F(PGA)* is the probability of experiencing a damage, *N* is the number of ground motion considered, therefore 20 in this study, and x_i is a Bernoulli random variable that indicates whether the structure is damaged or not where 0 indicates no damage and 1 indicate damage.

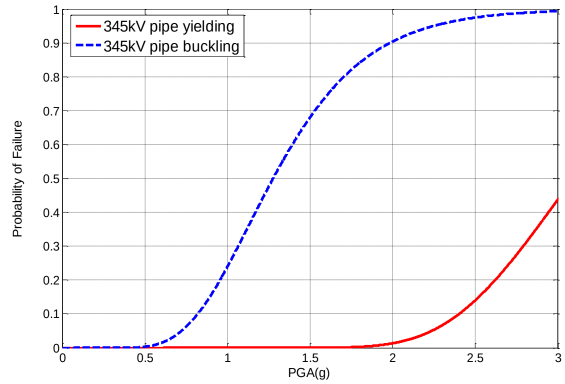
Two limit states for developing the fragility function are defined by the yielding in the axial direction and the elastic Euler buckling.

4.2. Seismic Fragility Curves of Transmission Towers

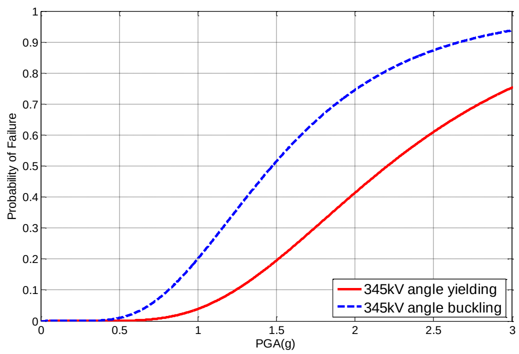
Seismic fragility curves are developed for four transmission towers according to the procedure described in the previous section as shown in Fig. 5. Blue and red lines are fragility curves with the yielding limit state and the buckling limit state, respectively. The medians and the standard deviations of the lognormal distribution function defined in eq. (1) are listed in Table 4. For 756 kV and 345 kV transmission towers, the buckling is more likely to happen before the yielding of the member occurs, while the opposite is observed for the 154 kV transmission tower.



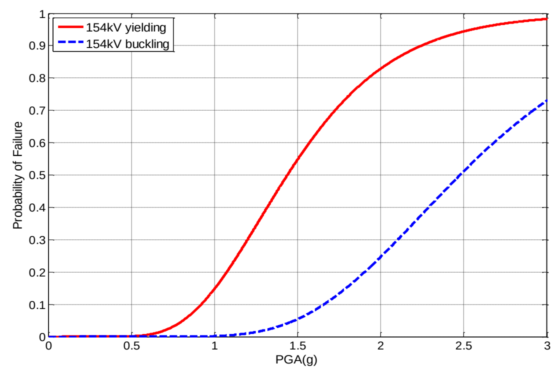
(a) Fragility curves of 765 kV transmission tower



(b) Fragility curves of pipe-type 345 kV transmission tower



(c) Fragility curves of pipe-type 345 kV transmission tower



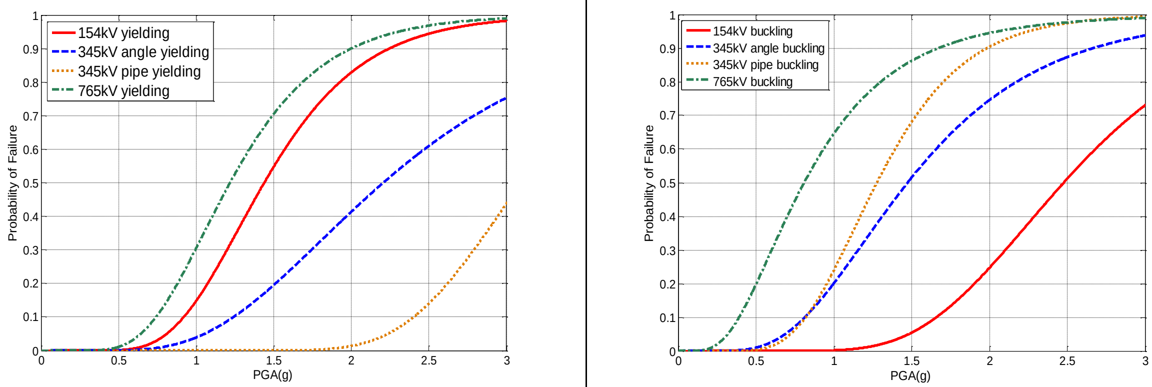
(d) Fragility curves of 154 kV transmission tower

Fig. 5 – Seismic fragility curves: (a) 765 kV, (b) pipe-type 345 kV, (c) angle-type 345 kV, and (d) 154 kV transmission towers.

Table 4 – Probability distribution parameters of fragility functions.

Limit State		$c(g)$	$\zeta\ (g)$
765kV pipe type	Yielding	1.2168	0.3872
	Buckling	0.8076	0.5678
345kV angle type	Yielding	2.2057	0.4487
	Buckling	1.4730	0.4632
345kV pipe type	Yielding	3.0926	0.1972
	Buckling	1.2749	0.3452
154kV angle type	Yielding	1.2168	0.3872
	Buckling	0.8076	0.5678

For all transmission towers, the probability of exceeding any of the two limit states is almost zero when PGA is less than 0.25 g for 756 kV, 0.70 g for angle-type 345 kV, and 0.5 g for pipe-type 345 kV and 154 kV transmission towers. To investigate the effect of the size of the transmission tower, fragility curves of different models are compared in Fig. 6. Not a clear relationship between the height of the transmission tower and the seismic vulnerability is observed for both limit states.



(a) Fragility curves with respect to the yielding limit state.	(a) Fragility curves with respect to the buckling limit state.

Fig. 6 – Comparison of seismic fragility curves: (a) yielding limit state and (b) buckling limit state.

5. Conclusions

Seismic fragility curves of transmission towers in South Korea are developed. Linear elastic finite element models of the transmission towers are developed for a series of time history analyses. For a set of 20 recorded ground motions are used to develop fragility curves. Limit states are defined in terms of the yielding and buckling of the structural members. The following conclusions are drawn.

- Transmission towers are safe under the design level earthquake in South Korea.
- For 756 kV and 345 kV transmission towers, the buckling is more likely to happen before the yielding of the member occurs, while the opposite is observed for the 154 kV transmission tower.
- Not a clear relationship between the height of the transmission tower and the seismic vulnerability is observed for both yielding and buckling limit states.

For more accurate investigation of the seismic performance of the transmission tower, a nonlinear time history analysis considering the soil-structure interaction will be required.

6. References

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