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Influence of multi-component ground motions on seismic responses of long-span transmission tower-line system: An experimental study

Li Tian[*1], Ruisheng Ma[1a], Canxing Qiu[1b], Aiqiang Xin[1c], Haiyang Pan[1c] and Wei Guo[2d]

[1]*School of Civil Engineering, Shandong University, Jinan, Shandong, 250061, China*
[2]*School of Civil Engineering, Central South University, Changsha, Hunan, 410075, China*

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Abstract. Seismic performance is particularly important for life-line structures, especially for long-span transmission tower line system subjected to multi-component ground motions. However, the influence of multi-component seismic loads and the coupling effect between supporting towers and transmission lines are not taken into consideration in the current seismic design specifications. In this research, shake table tests are conducted to investigate the performance of long-span transmission tower-line system under multi-component seismic excitations. For reproducing the genuine structural responses, the reduced-scale experimental model of the prototype is designed and constructed based on the Buckingham's theorem. And three commonly used seismic records are selected as the input ground motions according to the site soil condition of supporting towers. In order to compare the experimental results, the dynamic responses of transmission tower-line system subjected to single-component and two-component ground motions are also studied using shake table tests. Furthermore, an empirical model is proposed to evaluate the acceleration and member stress responses of transmission tower-line system subjected to multi-component ground motions. The results demonstrate that the ground motions with multi-components can amplify the dynamic response of transmission tower-line system, and transmission lines have a significant influence on the structural response and should not be neglected in seismic analysis. The experimental results can provide a reference for the seismic design and analysis of long-span transmission tower-line system subjected to multi-component ground motions.

Keywords: long-span transmission tower-line system; shake table tests; multi-component ground motions; empirical model

1. Introduction

It is widely acknowledged that power transmission tower-line system is categorized as a life-line structure which plays a significant role in the modern society. Unlike conventional civil structures, electricity transmission system consists of a group of supporting towers and transmission lines. Due to the long-distance transport of electricity, power transmission tower-line systems are required to cover almost all kinds of regions (unavoidably, the areas with seismicity). However, observations from past earthquakes have revealed that electricity transmission systems are more vulnerable to seismic excitation. For example, serious damages of transmission lines and collapses of transmission towers were both observed in the 1992 Landers earthquake, 1994 Northridge earthquake and 1995 Kobe earthquake (Hall e*t al.* 1994, Shinozuka 1995). In 1999, the Chi-Chi earthquake (NCREE 1999) had a serious impact on the electricity transmission system with 69 transmission lines destroyed, 15 towers collapsed and 26 towers tilted. During the 2008 Wenchuan earthquake, a wide range of electricity supply was disrupted due to the fact that more than 20 towers (110 kV) were completely collapsed and 10 towers (220 kV and 500 kV) were damaged severely. In 2012, the Yushu earthquake also caused serious damage to 35 kV electricity transmission systems. Fig. 1 illustrates the failure

Fig. 1 Failure of transmission towers in earthquakes

∗Corresponding author, Professor
E-mail: tianli@sdu.edu.cn
[a]Ph.D. Student
[b]Ph.D.
[c]M.D. Student
[d]Associate Professor

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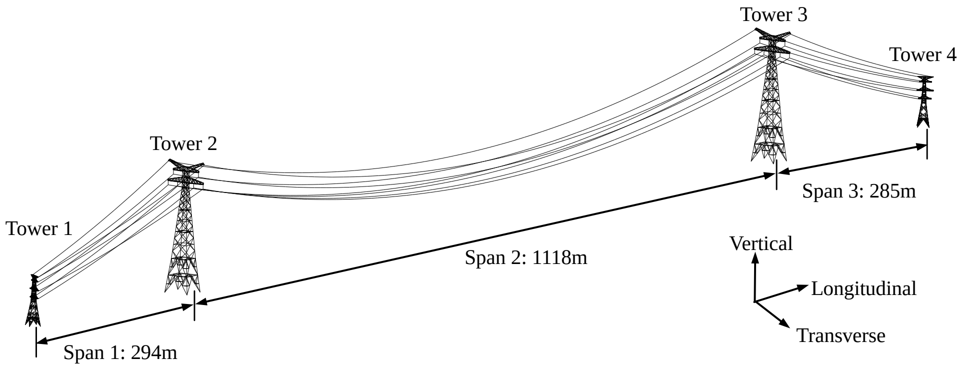


Fig. 2 Sketch of long-span transmission tower-line system

of transmission towers in earthquakes. Therefore, it is of great significance to improve the seismic capacity of long-span transmission tower-line system, and guarantee its safety and function during and after earthquake.

There are many research efforts dedicated to study the dynamic responses and ultimate capacity of power transmission tower-line system under earthquake excitations. Li *et al*. (2004, 2005) carried out a series of studies to investigate the seismic performance of power transmission tower-line system, and proposed a simplified method to calculate its structural responses. It was found that the influence of transmission line should not be ignored in seismic analysis. Lei and Chien (2009) investigated the structural behavior of electricity transmission system subjected to strong ground motions. The results showed that the contribution of transmission lines to the total seismic responses of structure was huge, and neglecting the effect of the wires would overestimate the ultimate strength of tower members. Besides these uniform earthquake excitations, some researchers also study the dynamic responses of electricity transmission system subjected to spatially varying ground motions. Ghobarah *et al*. (1996) investigated the effect of multi-support excitations on the lateral responses of transmission lines, which revealed that the assumption of uniform ground motions at all supports of a transmission line couldn't provide the most critical case for the response calculations. Bai *et al.* (2011) presented an investigation into the nonlinear responses of a coupled transmission tower-line system subjected to multi-component spatially varying ground motions. It was found that the spatially varying ground motions should be considered for a reliable seismic analysis and reasonable design. The influence of the spatial variation of seismic waves on dynamic responses of electricity transmission systems (straight line type and broken line type) were studied by Tian *et al.* (2012, 2014). The results indicated that the spatially varying seismic waves had a significant effect on the response of long-span transmission tower-line system, which was consistent with the above-mentioned conclusions. Wang *et al.* (2013), Tian *et al.* (2017a) further carried out the collapse analysis to study the ultimate capacity of power transmission tower-line system under earthquake excitations. In order to evaluate the seismic resistant design, Park *et al.* (2016) developed the seismic fragility curves of high voltage transmission towers in South Korea based on the limit states that were defined in terms of yielding and buckling of the structural members of supporting towers. Certainly, many research efforts have been made to study the dynamic responses of transmission tower-line system subjected to ground motions. However, quite limited experimental work has been completed for power transmission tower-line system, especially for long-span transmission tower-line system.

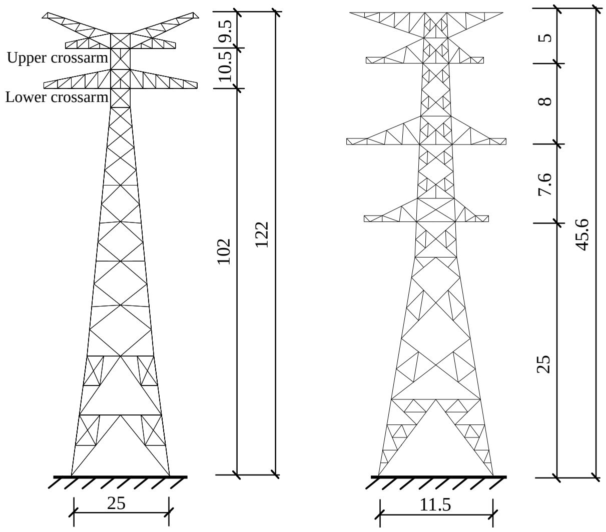
As a complement of previous works (Tian *et al.* 2016, Tian *et al.* 2017b), shake table tests are performed to investigate the dynamic responses of long-span transmission tower-line system subjected to multi-component in this paper. A reduced-scale model consisting of three spans of transmission lines and four supporting towers is designed and tested using an array of shake tables. Three commonly used seismic records are selected as the input ground motions of structure based on site soil condition. The structural responses of power transmission tower-line system subjected to single-component, two-component and multi-component ground motions are investigated and compared, respectively. To assess the acceleration and member stress responses of structure, an empirical model is further proposed based on the experimental results. The results obtained from this research can provide a basic database for the seismic analysis and design of long-span electricity transmission tower-line system.

2. Prototype transmission tower-line

A long-span transmission tower-line system across the Yellow River (the sixth longest river in the world) in the North of China is selected as a prototype for shake table test. Most of this transmission line is located in the 8-degree seismic design zone specified in the *Seismic Ground Motion Parameters Zonation Map of China* (GB 18306-2015 2015). Based on *Code for Seismic Design of Electrical Installations* (GB 50260-2013 2013), the Peak Ground Acceleration (PGA) adopted for the seismic design of this system is 0.2 g.

Fig. 2 illustrates the schematic diagram of the long-span transmission tower-line system. The prototype system includes four transmission towers (which are designated as Towers 1-4) and three spans of transmission line (which are

Fig. 3 Field picture of suspension-type tower (Towers 2 and 3)



(a) Towers 2 and 3 (b) Towers 1 and 4

Fig. 4 Elevation of transmission towers (m)

294, 1118 and 285 m long, respectively). As shown in Fig. 2, Towers 1 and 4 are tension-type tower which provides the transmission lines with tension force, while Towers 2 and 3 are suspension-type tower which just applies vertical force to transmission lines.

Fig. 3 gives the field picture of the suspension-type towers (i.e., Towers 2 and 3), which are the primary objective of this research. This kind of transmission tower consists of main members and diagonal members which are manufactured by Q345 and Q235 steel tubes, respectively. The elevations of two kinds of supporting tower are shown in Fig. 4. The total height of the suspension-type tower (Towers 2 and 3) is 122m, and each tower possesses two crossarms which are named as upper and lower crossarms respectively at the elevations of 112.5 m and 102 m (see Fig. 4). Two ground lines and conductor lines are supported at the upper crossarm, while four conductor lines are supported at the lower crossarm of structure. The ground line and conductor line are OPGW-180 and LHBGJ-400/95, respectively. Table 1 tabulates the detailed properties of conductor and ground lines.

Table 1 Properties of conductor and ground line

Category	Conductor line	Ground line
Designation	LHBGJ-400/95	OPGW-180
Outside diameter (mm)	29.14	17.85
Modulus of Elasticity (GPa)	78000	170100
Cross-section area (mm^2)	501.02	175.2
Mass per unit length (kg/km)	1856.7	1286
Thermal expansion coefficient (1/^{o}C)	18.0E-6	12.0E-6

3. Design of experimental model and instrumentation

The reduced-scale model of long-span transmission tower-line system is expected to be tested in the shake table laboratory of Central South University of China. This laboratory has an array of three 6-DOF shake tables which is suitable for the test of long-span structures. Each shake table has a payload of 30 ton, the size of 4 m×4 m, the maximum stroke of 250 mm, the maximum velocity of 1 m/s, the output frequency ranging from 0.1 Hz to 50 Hz, and the output acceleration up to 1.0 g along the horizontal directions. Moreover, the maximum permissible height for specimens is 15 m. Additionally, there are four towers in the reduced-scale model of the prototype, and only three shaking tables are available in the laboratory. Actually, this research primarily focuses on the responses of the towers supporting the long-span transmission lines. Thus, the Towers 2 and 3 are placed on the shake tables while Towers 1 and 4 are mounted on the floor of the laboratory.

Considering these limitations, a reduced-scale experimental model of long-span transmission tower is established. Since the same material (i.e., steel) is utilized to construct the experimental model, the scale factor for modulus of elasticity, S_E, is thus taken as 1.0. The scale factor for geometry, S_L, is assumed to be 1/20 due to the height limitation of the laboratory. As such, the heights of the experimental model of suspension-type (i.e., Towers 2 and 3) and tension-type (i.e., Towers 1 and 4) towers are scaled to 6.1 m and 2.28 m, respectively. Then, the scale factor for equivalent mass density of the transmission tower, S_ρ, is assumed to be 20. The scale factor for mass, S_M, can be therefore calculated by the following equation

$$S_M = S_\rho S_L^3 \tag{1}$$

It should be noted that artificial masses are added to the experimental models to satisfy the requirement from mass similarity (i.e., 1/400). Similarly, the scale factor for time (S_t), frequency (S_f), velocity (S_V) and acceleration (S_a) can be calculated by the following formulas

$$S_t = S_L \sqrt{\frac{S_\rho}{S_E}} \tag{2a}$$

$$S_f = 1 / S_t \tag{2b}$$

Table 2 Key scale factors of transmission towers

Quantity	Symbol	Value
Length	S_L	1/20
Modulus of elasticity	S_E	1
Poisson's Ratio	S_γ	1
Equivalent mass density	S_ρ	20
Equivalent mass	S_M	1/400
Stress	S_σ	1
Time	S_t	0.22
Displacement	S_r	1/20
Velocity	S_V	0.22
Acceleration	S_a	1
Frequency	S_f	4.47
Damping	S_c	1/89.4

$$S_V = \sqrt{\frac{S_E}{S_\rho}} \tag{2c}$$

$$S_a = \frac{S_E}{S_L S_\rho} \tag{2d}$$

Additionally, the scale factor for damping of the transmission towers can be expressed as follows (Zhou and Lu 2012)

$$S_c = S_\sigma S_L^{1.5} S_a^{-0.5} \tag{3}$$

in which, S_σ is the scale factor of stress of the transmission towers. One can solve S_C as 1/89.4 from Eq. (3). Table 2 tabulates the key scale factors of the transmission towers.

As for the transmission lines, the same scale factor (i.e., 1/20) as that of the transmission towers is preferably chosen. Designate such a design of experimental model as Scheme I. In this scheme, the middle span of the transmission lines reaches 55.9 m, which exceeds the space limitation of the laboratory. Considering this fact, an alternative scheme, denoted with Scheme II, is proposed for this research. A different scale factor will be utilized to help reduce the span length.

To quantify the differences between the Schemes I and II, the following modification factor λ is introduced

$$S_{L\,II}^T = \lambda S_{L\,I}^T \tag{4}$$

in which, $S_{L\,I}^T$ is the scale factor for span of transmission lines in Scheme I, which is equal to 1/20; $S_{L\,II}^T$ is the scale factor for span of transmission lines in Scheme II. λ is the modification factor, which is assumed to 0.5 in this research. According to Eq. (4), the scale factor for span of the transmission lines in Scheme II can be calculated, and it is equal to 1/40. Consequently, the length of Spans 1, 2 and 3 are scaled to 7.35 m, 27.95 m and 7.125 m, respectively. Therefore, the entire experimental model can be accommodated in the laboratory.

To realize the same stiffness of the transmission lines in Schemes I and II, the following requirement should be satisfied

Table 3 Mass per unit length of transmission lines

Transmission lines	Mass in prototype (g/m)	Mass in transmission line model (g/m)	Artificial mass to transmission line model (g/m)
Conductor	3713.4	64	307.34
Ground wire	1286	25	103.6

$$\frac{S_{E\,II}^T S_{A\,II}^T}{S_{L\,II}^T} = \frac{S_{E\,I}^T S_{A\,I}^T}{S_{L\,I}^T} \tag{5}$$

in which, $S_{E\,I}^T$ and $S_{E\,II}^T$ are the scale factors for modulus of elasticity of the transmission lines in Scheme I and II, respectively; $S_{A\,I}^T$ and $S_{A\,II}^T$ are the scale factors for cross-section area of the transmission lines in Scheme I and II, respectively.

For the Scheme I, the following relations hold

$$S_{A\,I}^T = S_L^2 \tag{6a}$$

$$S_{E\,I}^T = S_E \tag{6b}$$

Substituting Eqs. (4), 6(a) and (b) into Eq. (6), one obtains

$$S_{A\,II}^T = \frac{\lambda S_L^2}{S_{E\,II}^T} \tag{7}$$

According to the Eq. (7), the diameters of conductor and ground wires can be calculated, which are equal to 3.56 mm and 2.19 mm, respectively. Moreover, to achieve same mass similarity in Schemes I and II, the following requirement should be satisfied

$$S_{M\,I}^T = S_{M\,II}^T S_{L\,II}^T \tag{8}$$

in which, $S_{M\,I}^T$ and $S_{M\,II}^T$ are the scale factors for mass of the transmission lines in Scheme I and II, respectively. Table 3 tabulates the artificial mass added to the experimental model of transmission lines.

For transmission lines, the vibration frequencies primarily depend upon its sag, which can be expressed as follows

$$S_{f\,II}^T = 1/\sqrt{S_{d\,II}^T} \tag{9}$$

in which, $S_{f\,II}^T$ is the scale factor for vibration frequency of the transmission lines in Scheme II; and $S_{d\,II}^T$ is the scale factor for the sag of the transmission lines in Scheme II. According to Eq. (9), $S_{d\,II}^T$ is calculated and its value is equal to 4.47.

Moreover, the scale factors for damping of the transmission line in Scheme I and II can be calculated according to Eq. (3), and they are equal to 1/89.4 and 1/253, respectively. Obviously, Scheme I is a good choice from the point of scaled damping. However, as mentioned above, the middle span length of the transmission lines in Scheme I reaches 55.9 m, which exceeds the space limitation of the laboratory. This means that Scheme I is not feasible for the long-span transmission tower-line system. In Scheme II, the

Table 4 Key scale factors of transmission lines

Quantity	Symbol	Value
Length	S_L^T	1/40
Acceleration	S_a^T	1
Mass of transmission lines	S_M^T	1/400
Frequency of transmission lines	S_f^T	4.47
Modulus of elasticity of transmission lines	S_E^T	1
Mass density of transmission lines	S_ρ^T	1/10
Damping in Scheme I	$S_{c\ I}^T$	1/89.4
Damping in Scheme II	$S_{c\ II}^T$	1/253
Sag	$S_{d\ II}^T$	4.47

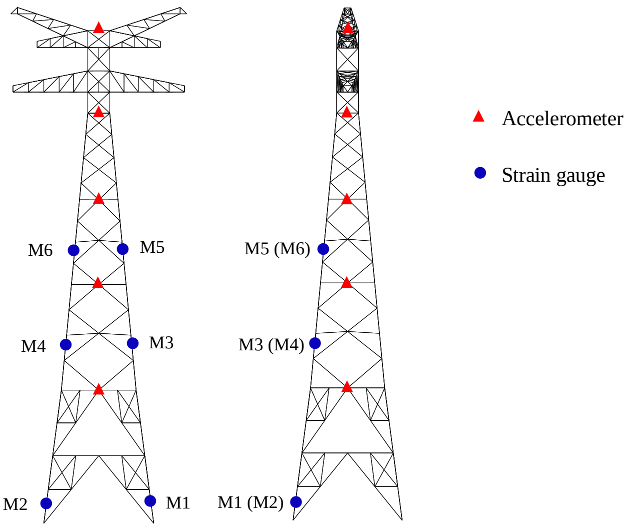
(a) Tower 2 of the experimental model

(b)Transmission lines of the experimental model

Fig. 5 Experimental model of the transmission tower-line system

length of middle span is 27.95 m which can satisfy the space limitation of laboratory. Considering these facts comprehensively, Scheme II is finally adopted for the experimental model of the transmission lines by sacrificing the damping to some extent. Key scale factors of transmission lines are tabulated in Table 4.

As shown in Fig. 5, the experimental model of the long-span transmission tower-line system is given. The wall thickness and diameter of the steel tubes used in the experimental models of Towers 2 and 3 vary from 0.25 mm to 0.6 mm and from 4 mm to 31 mm, respectively. To satisfy the requirement from mass similarity, iron rings are fixed on the main members of the experimental models of



(a) Elevation (b) Sideview

Fig. 6 Instrumentation of Towers 2 and 3

Towers 2 and 3 (see in Fig. 5(a)). Steel wires with the diameters of 3.56 mm and 2.19 mm are utilized for the ground lines and conductor lines in the experimental model, respectively. Stainless steel chains are installed along each steel wire to reach the target artificial mass (see in Fig. 5(b)).

As described above, Towers 2 and 3 supporting the long-span transmission lines are the primary research objective in this paper. Therefore, these two towers are chosen for instrumentation. The acceleration and stress responses of the transmission towers are recorded. Fig. 6 shows the instrumentations of Towers 2 and 3. It can be seen that the accelerometers are installed along the height of the transmission tower, and both longitudinal and transverse acceleration responses are recorded. The strain gauges are attached on the selected main members of the towers. Note that the same instrumentations are adopted for Towers 2 and 3.

4. Selection of ground motions and test condition

The site of the transmission tower-line system is classified as class II. Based on the *Code for Seismic Design of Electrical Installations* (GB 18306-2015 2015), three typical natural seismic records are selected in this section. Table 5 lists the detailed information of these seismic records. It can be found that each seismic record has two horizontal components and one vertical component. Compared with its transverse direction, the longitudinal direction of the transmission tower-line system is more adverse. Therefore, for each seismic record, the horizontal component with larger PGA (such as, the S00E component of 1940 Imperial Valley seismic record) is input along the longitudinal direction (see Fig. 2) of the long-span transmission tower-line system, and another horizontal component, i.e., the one with smaller PGA, is applied along the transverse direction of the system (see Fig. 2). Moreover, the vertical component of seismic wave (such as,

Table 5 Summary of shake table tests

Test ID	Structure	Earthquake	Longitudinal direction	Transverse direction	Vertical direction
1	Tower-line	1940 Imperial Valley	S00E	S90W	VERT
2	Tower-line	1952 Kern County	TAF111	TAF021	TAF-UP
3	Tower-line	1994 Northridge	BLD090	BLD360	BLD-UP
4	Tower-line	1940 Imperial Valley	S00E	S90W	-- [a]
5	Tower-line	1952 Kern County	TAF111	TAF021	-- [a]
6	Tower-line	1994 Northridge	BLD090	BLD360	-- [a]
7	Tower-line	1940 Imperial Valley	S00E	-- [a]	-- [a]
8	Tower-line	1952 Kern County	TAF111	-- [a]	-- [a]
9	Tower-line	1994 Northridge	BLD090	-- [a]	-- [a]
10	Single tower	1940 Imperial Valley	S00E	S90W	VERT
11	Single tower	1952 Kern County	TAF111	TAF021	TAF-UP
12	Single tower	1994 Northridge	BLD090	BLD360	BLD-UP

[a] Not applicable.

the VERT component of 1940 Imperial Valley seismic record) is input along the vertical direction of this system. Note that the maximum PGA of each seismic record is adjusted to 0.2 g, and the accelerations of the other two components are scaled using the same proportion.

As summarized in Table 5, a total of twelve shake table tests are conducted. For each seismic record, single-component (No 7-9), two-component (No 4-6) and multi-component (No 1-3) ground motions are applied to test the responses of long-span transmission tower-line system, respectively. To compare with the responses of the coupled system, the dynamic responses of single supporting tower subjected to multi-component ground motions are also investigated in shake table tests (No 10-12). As shown in Fig. 7, the responses spectra of these seismic records with the damping ratio of 2% are also generated to realize its energy distribution in frequency domain.

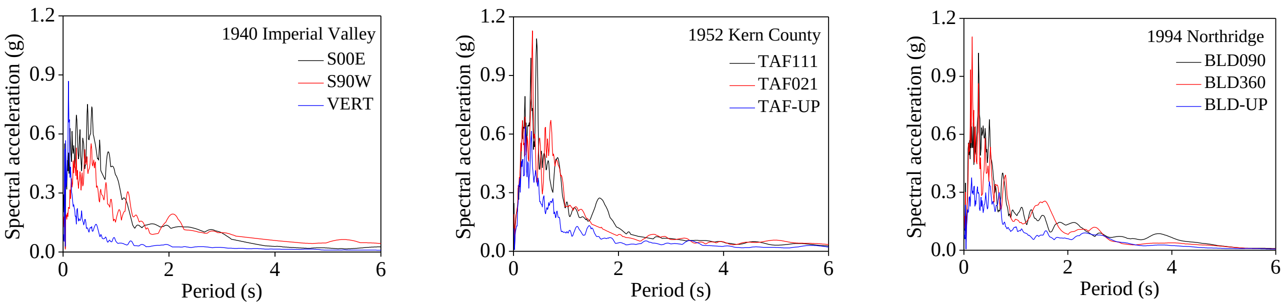
5. Results and discussions

According to the above-mentioned test plan, the shake table tests of the experimental model are performed. Before each test, the white noise excitations are utilized to obtain the fundamental frequencies of the experimental model in the longitudinal and transverse directions. The fundamental frequencies of the system along longitudinal and transverse direction are 6.63 Hz and 6.67 Hz, respectively. It is found that the fundamental frequencies of the experimental model in the longitudinal and transverse directions remain constant during the tests, suggesting that the system remains fully elastic throughout the shake table tests. Note that the scale factors of acceleration and stress response of the transmission tower are equal to 1.0 (see Table 3), thus the acceleration and stress responses obtained in shake table tests are the same as the actual responses of the prototype.

5.1 Transmission tower-line system under multi-component ground motions

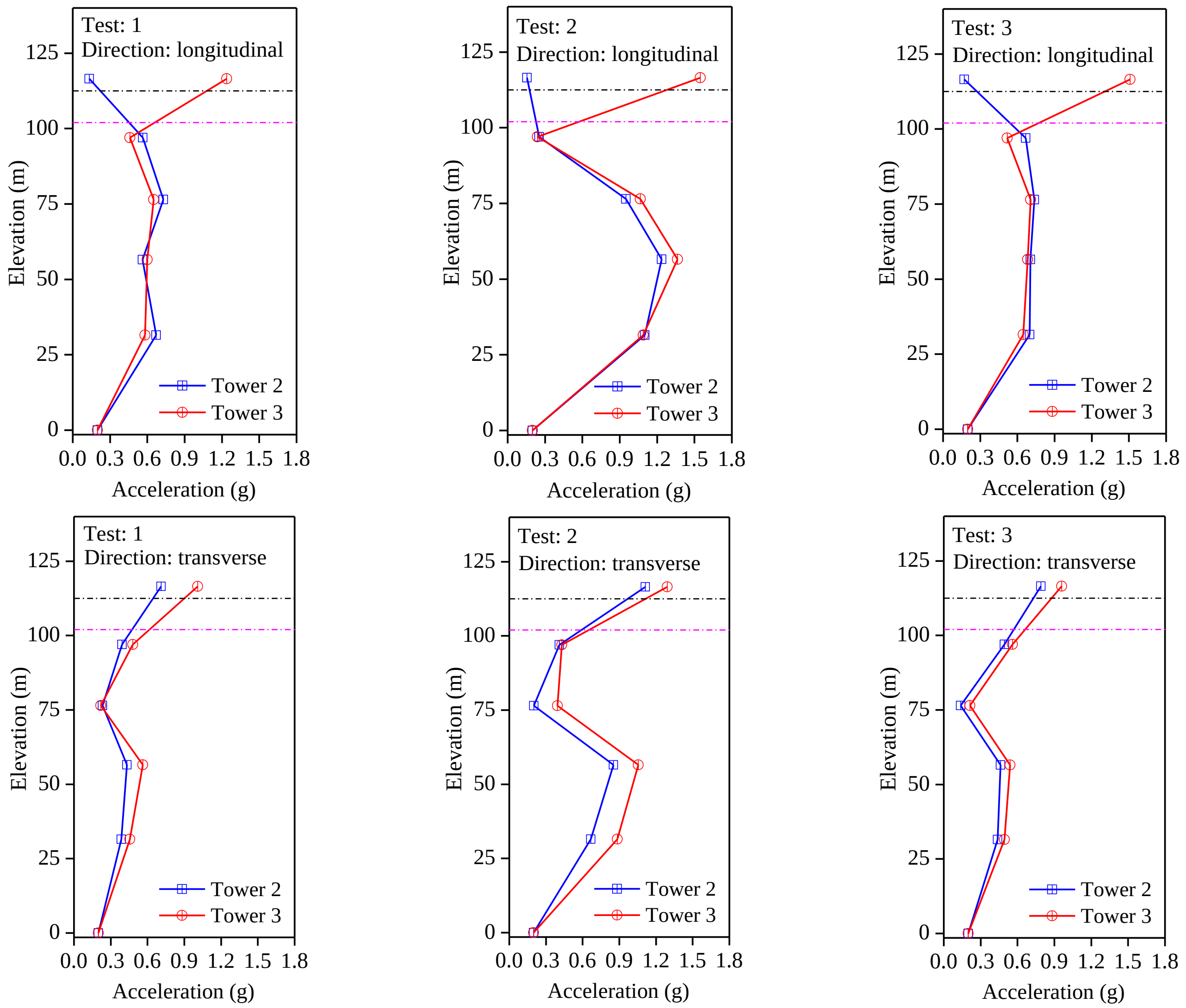
As listed in Table 5, Tests 1-3 are conducted to investigate the responses of the long-span transmission tower-line system subjected to multi-component ground motions. Fig. 8 shows the comparison between the peak acceleration responses of Towers 2 and 3. It is observed that the longitudinal acceleration responses of these two towers are different, while the transverse acceleration responses are similar. This phenomenon can be attributed to the fact that the coupling effect between the transmission towers and transmission lines is strong in the longitudinal direction, but this coupling effect is weak in the transverse direction. Owing to the influence of the transmission lines, the longitudinal acceleration responses of both towers at the upper crossarm (see in Fig. 4) are significantly different. The comparison between the stress responses of the selected main member of Towers 2 and 3 is illustrated in Fig. 9. It can be found that the stress responses of Towers 2 and 3 are not identical. This is primarily due to the fact that the transmission lines are quite flexible and cannot generate compatible deformations between the two towers.

The test results from Tests 1-3 suggest that it is necessary to consider the coupling effect between



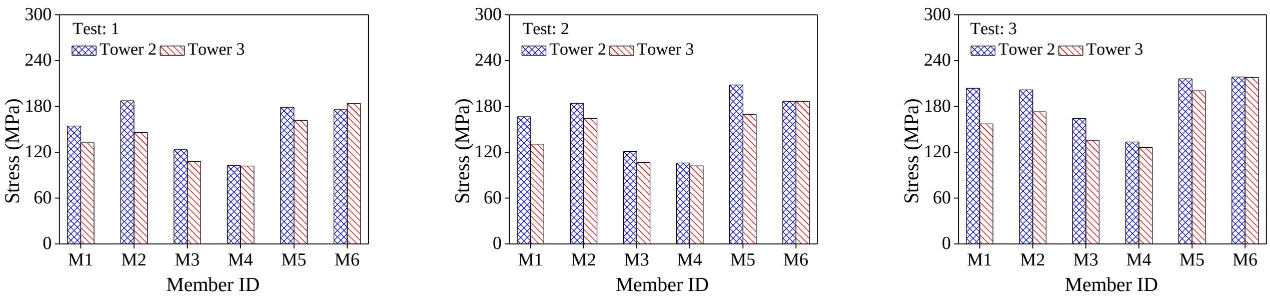
(a) Imperial Valley (b) Kern County (c) Northridge

Fig. 7 Response spectra of the ground motions used in the tests



(a) Test 1 (b) Test 2 (c) Test 3

Fig. 8 Comparison of the peak acceleartion resposnes of Towers 2 and 3



(a) Test 1 (b) Test 2 (c) Test 3

Fig. 9 Comparison of main member stresses of Towers 2 and 3

transmission towers and transmission lines, and geometrical nonlinearity of transmission lines for the seismic analysis and design of power transmission tower-line system.

5.2 Transmission tower-line system under two-component ground motions

Tests 4-6 (listed in Table 5) are carried out to investigate the responses of Towers 2 and 3 subjected to two-component ground motions. To quantify the response difference, the response comparison factor $\beta_{\mathrm{R.ij}}$ is used hereinafter, which defined as the ratio of the response from test i to that of test j. The subscript R represents a response quantity of interest (which can be replaced by A and σ for the peak acceleration value and member stress value, respectively), and the subscripts of i and j represent the IDs of the two tests considered in the comparison. As defined, a $\beta_{\mathrm{R.ij}}$ value larger than 1.0 indicates that the response from

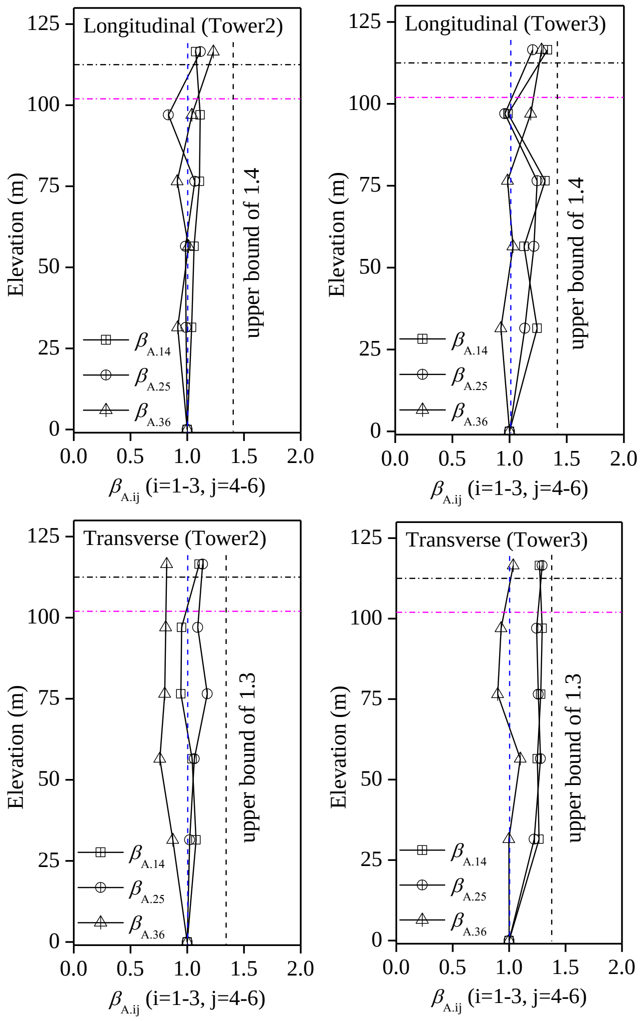


Fig. 10 Comparison of $\beta_{A.ij}$ (i=1-3, j=4-6)

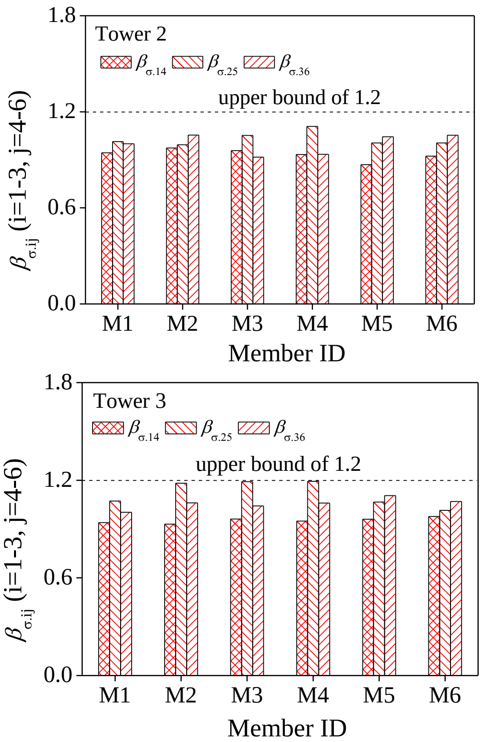


Fig. 11 Comparison of $\beta_{\sigma.ij}$ (i=1-3, j=4-6)

test i is higher than that of test j and vice versa.

Fig. 10 shows the comparison of $\beta_{A.ij}$ (i=1-3, j=4-6). Compared with two-component seismic excitations, larger acceleration responses are found for the system subjected to multi-component ground motions. It can be found that the $\beta_{A.ij}$ (i=1-3, j=4-6) vary along the height of the towers and are different between the longitudinal and transverse directions. Both the longitudinal and transverse $\beta_{A.ij}$ values (i=1-3, j=4-6) are not identical for the system subjected to different seismic ground motions. The $\beta_{A.ij}$ (i=1-3, j=4-6) along the structural height are amplified except for individual measuring points in the longitudinal direction. However, the $\beta_{A.ij}$ (i=1-3, j=4-6) along the structural height may be amplified or reduced with the change of seismic wave in the transverse direction. The upper bound values of the $\beta_{A.ij}$ (i=1-3, j=4-6) are 1.4 and 1.3 in the longitudinal and transverse directions, respectively.

Fig. 11 illustrates the comparison of $\beta_{\sigma.ij}$ (i=1-3, j=4-6). Similar with the acceleration response, the stress response comparison factor $\beta_{\sigma.ij}$ (i=1-3, j=4-6) are different between the longitudinal and transverse directions. As shown in Fig. 11, the factor $\beta_{\sigma.ij}$ can be either amplified or reduced when the system subjected to different ground motions. Compared with the $\beta_{\sigma.ij}$ (i=1-3, j=4-6) of Tower 2, Tower 3 has higher values. However, the upper bound value of $\beta_{\sigma.ij}$ (i=1-3, j=4-6) is 1.2 for both towers.

The above observations demonstrate that the responses of the experimental model under two-component ground motions may be larger or smaller than those under multi-component ground motions, but the upper bound values of the response comparison factors are always larger than 1.0. Therefore, it is of great importance to consider the multi-component ground motions in the seismic design and analysis of long-span transmission tower-line system.

5.3 Transmission tower-line system under single-component ground motion

As tabulated in Table 5, Tests 7-9 are conducted to study the responses of the experimental model subjected to single-component ground motion. Note that the single-component ground motions are applied along the longitudinal direction of the system as described above. The comparisons of $\beta_{A.ij}$ are illustrated in Fig. 12. As shown, both acceleration responses of Towers 2 and 3 subjected to multi-component ground motions are larger than those of the system subjected to single-component ground motions. Moreover, the acceleration response comparison factors $\beta_{A.ij}$ of Tower 3 are higher than those of Tower 2. The maximum amplification are found at the top of Tower 3 and the upper bounds of the $\beta_{A.ij}$ (i=1-3, j=7-9) are identified to be 1.5 for both the longitudinal and transverse directions.

Fig. 13 shows the stress response comparison factors, $\beta_{\sigma.ij}$ (i=1-3, j=7-9). Compared with single-component seismic excitation, the stress responses of the system subjected to multi-component ground motions are amplified significantly. Due to the difference of seismic records, the

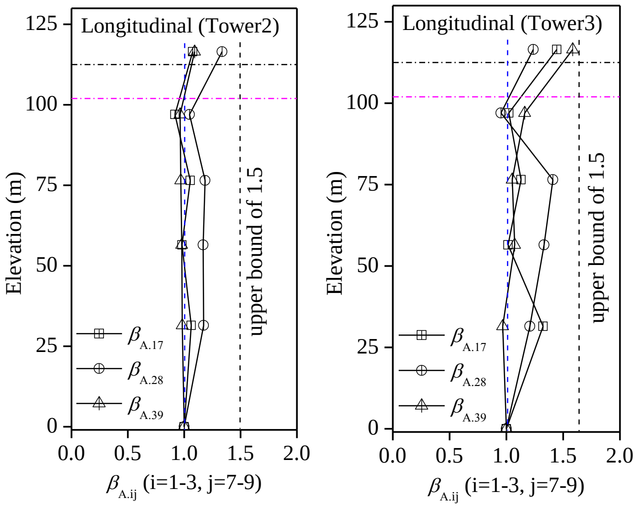


Fig. 12 Comparison of $\beta_{A.ij}$ (i=1-3, j=7-9)

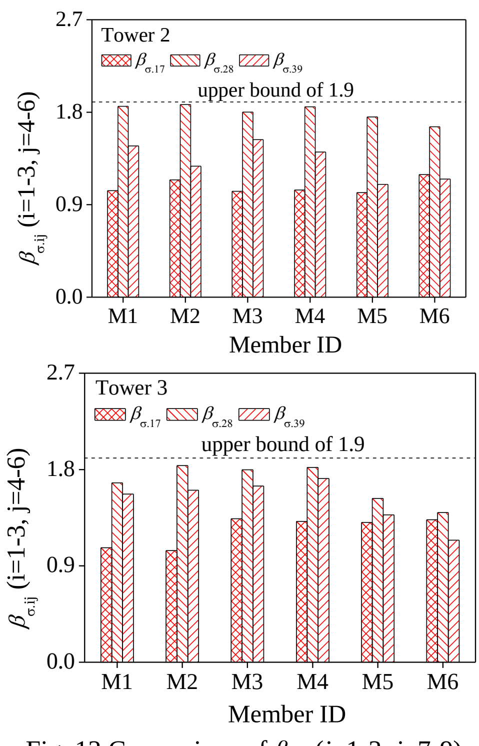


Fig. 13 Comparison of $\beta_{\sigma.ij}$ (i=1-3, j=7-9)

amplification factors of each seismic record are not identical. And the amplification factors of Towers 2 and 3 subjected to the same ground motion are also different. However, the upper bounds of Towers 2 and 3 are very approximate, and the upper bound of the $\beta_{\sigma.ij}$ (i=1-3, j=7-9) can be identified as 1.9.

The results from Tests 7-9 indicate that the responses of the experimental model under multi-component ground motions are great larger than those under single-component ground motion. Therefore, the responses of the transmission towers will be severely underestimated if only single-component ground motion is considered.

5.4 Transmission tower-line system vs single tower

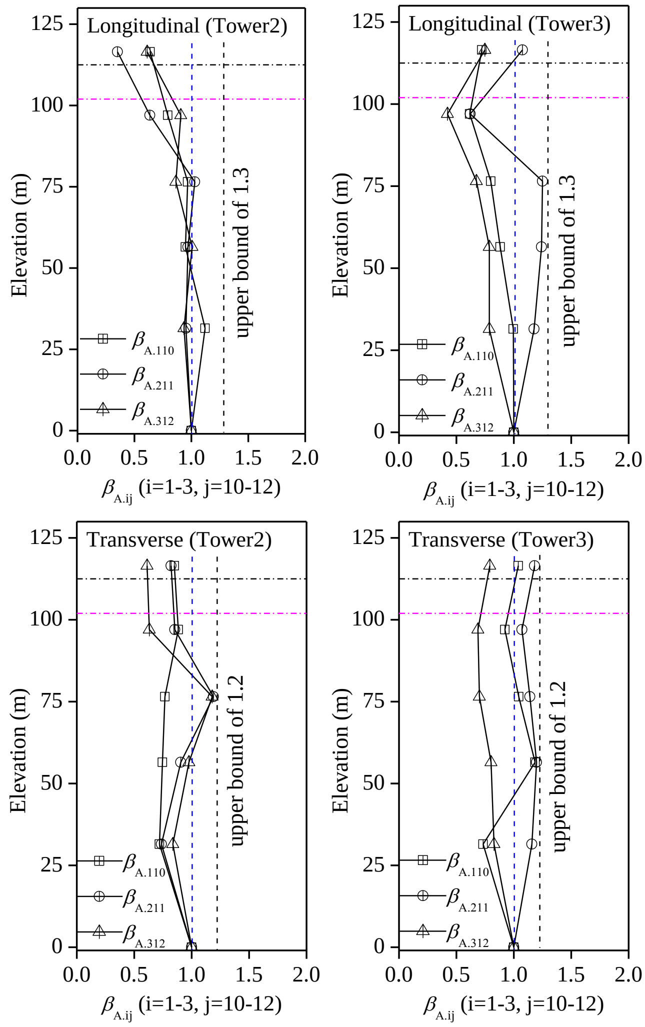


Fig. 14 Comparison of $\beta_{A.ij}$ (i=1-3, j=10-12)

To compare with the responses of transmission tower-line system, Tests 10-12 (listed in Table 5) are conducted to investigate the responses of transmission tower subjected to multi-component ground motions. The acceleration response comparison factors $\beta_{A.ij}$ are shown in Fig. 14. It can be observed that the acceleration responses of transmission tower can be either increased or decreased compared with those of power transmission tower-line system. However, most comparison factors $\beta_{A.ij}$ are less than 1.0, indicating that the acceleration responses of the transmission tower are larger than those of the transmission tower-line system and transmission lines have a significant influence on the dynamic responses of the system. In other words, the transmission lines have a function of reducing dynamic responses of the transmission towers. Another reason is that the transmission line increases the damping of the system, so the effect of transmission lines would decrease the response of the tower. Moreover, the acceleration response comparison factors $\beta_{A.ij}$ of Tower 3 along longitudinal direction are much more remarkable than those of Tower 2 while the comparison factors of both towers along the transverse direction are very approximate. The upper bound values of $\beta_{A.ij}$ (i=1-3, j=10-12) are taken

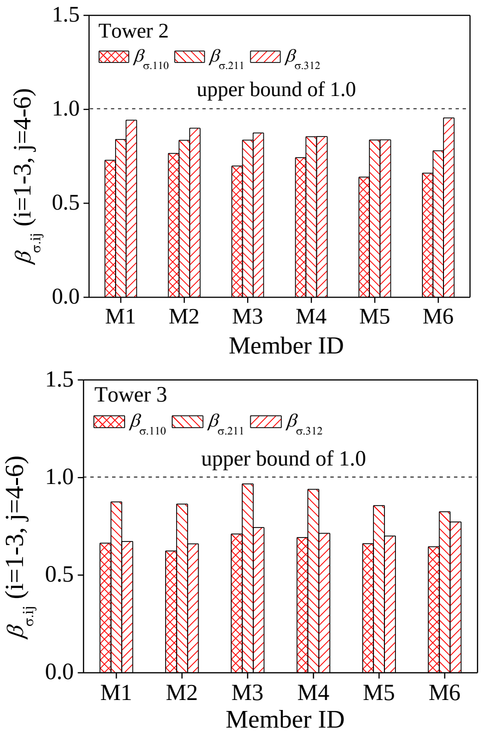


Fig. 15 Comparison of $\beta_{\sigma.ij}$ (i=1-3, j=10-12)

as 1.3 and 1.2 in the longitudinal and transverse direction, respectively.

Fig. 15 illustrates the stress response comparison factor $\beta_{\sigma.ij}$ of the selected main members of Towers 2 and 3. As shown in Fig. 15, all values of $\beta_{\sigma.ij}$ are below 1.0, suggesting that the stress responses of transmission tower-line system are smaller than those of the transmission tower. This phenomenon further verified the vibration reduction function of the transmission lines. The maximum amplification of Towers 2 and 3 are similar and close to 1.0, thus the upper bound values of $\beta_{\sigma.ij}$ (i=1-3, j=10-12) are identified to be 1.0.

Based on the above discussion, the transmission lines have a significant influence on the acceleration and stress responses of the transmission towers subjected to multi-component ground motions. Neglecting the effect of transmission lines, the seismic resistant capacity of transmission tower may be underestimated in the seismic design and analysis.

6. Empirical model for design recommendation

As discussed in Section 5, the responses of the transmission tower-line system are quite different when the system is subjected to multi-component, two-component and single-component ground motions. For the convenience of design, an empirical model is established to obtain the responses of power transmission tower-line system subjected to multi-component ground motions, which can be expressed as follows

$$R = \alpha_i R_0 \tag{10}$$

Table 6 Recommended values for amplification factor

α_i	Amplification factor		
	Acceleration response		Member stress
	Longitudinal	Transverse	
α_1	1.4	1.3	1.2
α_2	1.5	--[a]	1.9
α_3	1.3	1.2	1.0

[a] Not applicable.

where, R is the response of transmission tower-line system under multi-component ground motions; R_0 is the response of transmission tower-line system subjected to two-component or single ground motions, or the responses of transmission tower subjected to multi-component ground motions. α_i is the amplification factor according to different test conditions.

The amplification factor α_i can be obtained from the upper bound values shown in Figs. 10-15. Table 6 presents the recommended values for the amplification factor. It can be seen from Table 6 that α_1 and α_2 are the amplification factor for the responses of transmission tower-line system subjected to two-component and single-component ground motions, respectively. And α_3 is the amplification factor for the responses of single transmission tower subjected to multi-component ground motions. The amplification factor can provide a simple method for the seismic design and analysis of transmission tower-line system subjected to multi-component ground motions.

7. Conclusions

This research focuses on the responses of long-span transmission tower-line system subjected to multi-component ground motions. A reduced-scale experimental model of the prototype is tested using an array of shake tables. The responses of experimental model subjected to multi-component, two-component and single-component ground motions are investigated, respectively. To study the influence of transmission lines, the responses of the transmission tower are also investigated using shake table tests. Furthermore, an empirical model is proposed to evaluate the acceleration and member stress responses of the power transmission tower-line system subjected to multi-component ground motions. Based on the experimental database analysis, the following conclusions are drawn:

- The coupling effect between the supporting towers and transmission lines is significant and has a great influence on the responses of the supporting towers. The influence of the coupling effect is more remarkable along longitudinal direction than the transverse direction of the system. This coupling effect should be considered in the seismic design of long-span transmission tower-line system.
- For two-component and single-component ground motions, most upper bound values of the response comparison factors are larger than 1.0. In other words,

the responses of the transmission tower-line system subjected to multi-component are generally larger than those of the system subjected to two-component or single-component ground motions. Therefore, multi-component seismic excitation should be adopted to evaluate the seismic performance of long-span transmission tower-line system.

• The transmission lines have a significant influence on the acceleration and stress responses of the transmission towers subjected to multi-component ground motions. Neglecting the effect of transmission lines, the seismic resistant capacity of transmission tower may be underestimated in the seismic design and analysis.

• The proposed empirical model provides a simple method to evaluate the performance of power transmission tower-line system subjected to multi-component ground motions. The recommended values of the amplification factor are determined based on the experimental results and can serve as a practical reference for the seismic design and analysis of long-span transmission tower-line system.

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