16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 946 (Abstract ID)

Registration Code: S- 1465889881

Seismic Performance Study of Composite Insulator Assembled in 1 000 kV Capacitor Voltage Transformer by Quasi-static Test and Shaking Table Test

Sheng Li(1), Yongfeng Cheng(2), Zhicheng Lu(3), Zhubing Zhu(4), Min Zhong(5)

(1) *Beijing, China, China Electric Research Institute, lisheng@epri.sgcc.com.cn*
(2) *Beijing, China, China Electric Research Institute, cyf@epri.sgcc.com.cn*
(3) *Beijing, China, China Electric Research Institute, luzc@epri.sgcc.com.cn*
(4) *Beijing, China, China Electric Research Institute, zhuzb@epri.sgcc.com.cn*
(5) *Beijing, China, China Electric Research Institute, zhongmin@epri.sgcc.com.cn*

Abstract:

Insulators are main structural elements for many kinds of equipment in electrical substations. Traditionally, insulators used in substations are made of porcelain, which are vulnerable in earthquake events due to the brittleness of porcelain material. In recent years, insulators made of fiberglass reinforced polymer have gained great importance for better mechanical properties. However, studies on seismic performance of electrical equipment which assembles composite insulators are still limited. This paper studies mechanical properties and seismic performance of hollow core composite insulators by impact test, quasi-static bending test and shaking table test. Full scale composite insulators assembled in 1 000 kV capacitor voltage transformer, which is so for the highest voltage level, are taken as specimens. Flexural stiffness, vibration modes and damping ratio are obtained from bending test and impact hammer test of composite insulators. Failure mode of the insulator under static bending load is observed, which is mainly failure of metallic flange. These parameters are employed in seismic modeling of the 1 000 kV capacitor voltage transformer and seismic response of the equipment is analyzed. In the last, shaking table test of the equipment is carried out as validation, which proves that the numerical model built in this paper has a high overall accuracy in seismic response prediction. The study gains insights on the performance of composite insulators and provides an example for seismic performance evaluation of composite insulators, which are meaningful seismic design of electrical substation. The study also points out that increasing the strength of metallic flange should be a major consideration for further seismic performance improvement of composite insulators in this scale.

Key words: shaking table test, quasi-static test, electrical equipment, composite insulator, capacitor voltage transformer

1 Introduction

As an important part in electrical power system, electrical substation performs functions in making electrical power ready for long distance transmission and being available for consumers. Seismic failure of substation in high voltage electrical grid may result in the shunting down of power supply in vast area after earthquake, which will cause difficulties for disaster mitigation efforts. In electrical substation, a large amount of equipment assembles insulators as load carrying structure. Traditional insulators are made of porcelain [1], which are heavy and brittle. A typical value for allowable tension stress of porcelain insulator is 45 MPa, and it seldom reaches 80 MPa. Seismic capacity of equipment made of porcelain insulators becomes a major weakness for seismic performance of substation [2, 3]. Fig.1 shows the seismic failure of porcelain insulator in 2008 Wencuan earthquake. For substation in ultra-high voltage (UHV) level, equipment is designed in larger weight and height, but the strength of porcelain does not increase. In this way, seismic safety of UHV substation becomes more challenging [4].

Fig. 1 Failure of porcelain insulator in 2008 Wencuan earthquake

Composite insulators, also known as polymer insulators, are made of fiberglass reinforced polymer with silicone rubber sheds, as seen in Fig 2. The adoption of composite insulator in ultra-high voltage substation equipment, as seen in Fig. 3, is expected to enhance seismic performance of the substation. However, due to a relatively short history in field service [5], research on seismic performance of composite insulator, particularly for composite insulators used in ultra-high voltage substation, is still limited.

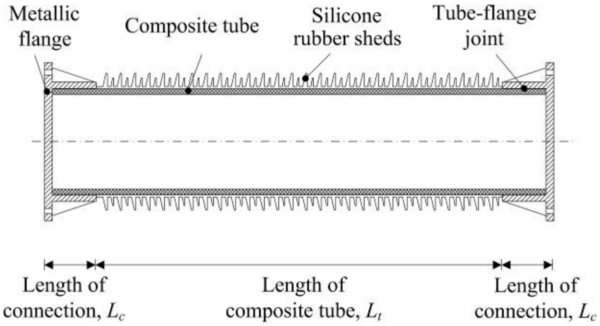


Fig.2 Section of a composite insulator

Fig. 3 Electrical equipment assembled with composite insulator in substations

Quasi-static bending test, impact hammer test and shaking table test are major experimental methods to study the mechanical and seismic performance of composite insulator. Bonhôte [6]， Prenleloup [7] and Kumosa [8, 9] carried out several static test of composite insulator to study the stress and failure mode of composite–metallic flange joints and developed 3-D finite element model to carefully examine the stress at interface between composite and metallic flange. Roh [10] carried out both impact test and static bending test of a hollow core composite insulator. Numerical model was built to model the strength, damping and global behavior of the insulator. Epackachi [11] examined force–displacement relationship, stiffness and strength deteriorations of full scale hollow core composite insulator by static cyclic quasi-static tests and impact hammer test. Anshel [12] tested the composite insulator in a series of loading case with incremental peak ground acceleration (PGA), and observed nonlinear characteristics in seismic response. Fahad [13] tested composite transformer bushing on shaking table and developed modeling technique for seismic response analysis based on test results.

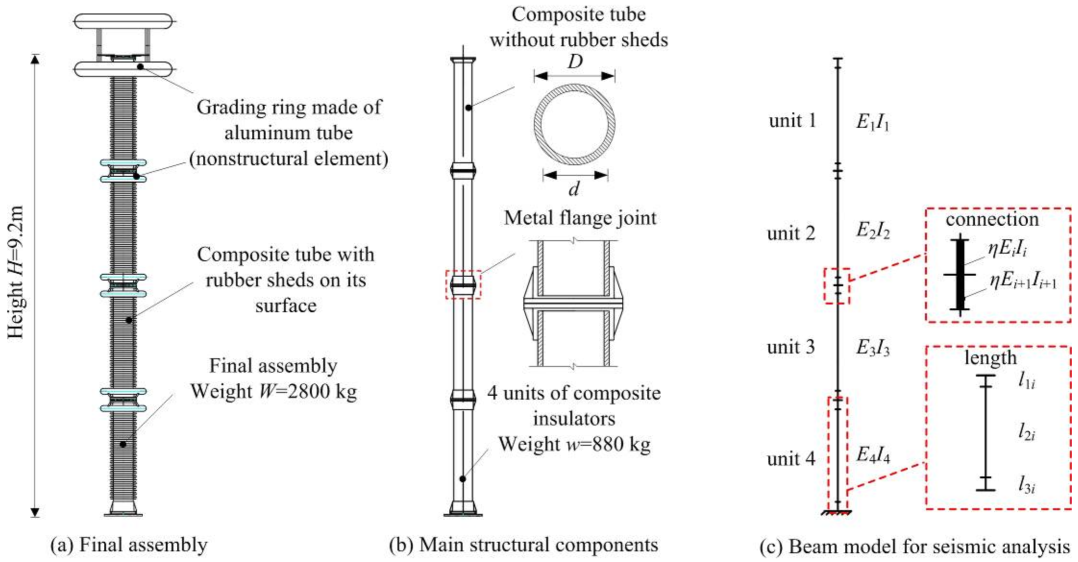
This paper carried out impact hammer test, quasi-static bending test and shaking table test to composite insulators used in 1 000 kV ultra-high voltage Capacitor Voltage Transformer (CVT). Results obtained from bending test and impact hammer test were adopted in seismic analysis. Then, shaking table test was carried out to validate the numerical results. In this way, this paper proposed a method to evaluate seismic performance of composite equipment with results from bending test and impact hammer test. This is meaningful when taking the high cost of organizing full scale shaking table test into consideration. The study also points out that increasing the strength of metallic flange should be a major consideration for further improvement of seismic performance of composite insulator.

2 Mechanical test of composite insulators

Flexural rigidity and damping are important aspects for seismic performance analysis of composite insulator. In this part, quasi-static bending test and impact hammer test were carried out to study flexural rigidity and damping of composite insulators assembled in 1 000 kV capacitor voltage transformer.

2.1 structural parameters and analytical model

Capacitor voltage transformer is a typical kind of slender equipment in substation, which contains an assembly of insulators as main load carrying structure. Fig 4 (a) is the schematic diagram of capacitor voltage transformer adopted in this study, which is the equipment in final assembly state. The mass distribution of the equipment along the center line can be found on product specification, and the weight of final assembly is 2800 kg, containing all structural and nonstructural components, such as rubber sheds outside the composite tube and aluminum grading ring at the top and middle of the equipment. Fig 4 (b) is an assembly of 4 composite insulators, which is the loading carrying structure of the equipment. Each composite insulator contains fiber glass tube and aluminum flange fixed at both ends, and other nonstructural components are not included. The section for unit 1 and 2 is 378 mm in diameter and 16 mm in thickness, and the section for unit 3 and 4 is 395 mm in diameter and 25 mm in thickness. The weight of composite insulators is 880 kg.



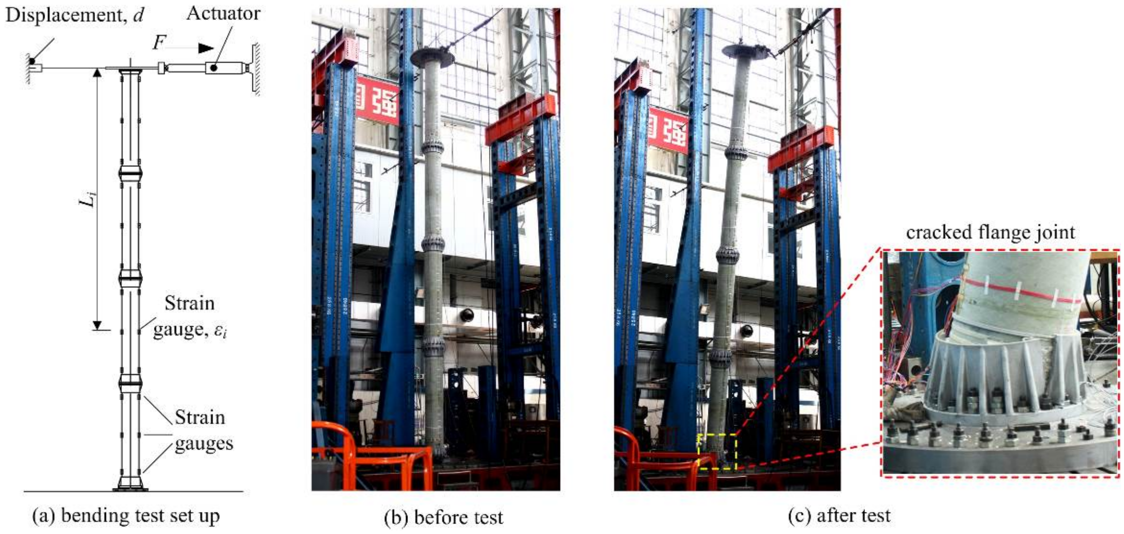
(a) Final assembly (b) Main structural components (c) Beam model for seismic analysis

Fig. 4 Capacitor voltage transformer and its main structure

The analytical model of composite insulators is built as Fig. 4(c), which is a beam element model built for seismic analysis. It is noteworthy that for fiberglass reinforced polymer tube, the elastic modulus of composite material may vary for different tubes, so it is necessary to assume different rigidity values E_iI_i for each tube section. For flange joint between two insulator units, it is hard to find an a precise value for the bending stiffness in length of joint, considering the complex properties of contact surfaces between metal flange and composite tube, as well as bolted flange connection between flanges. Assume a factor η to considering these uncertainties, then, the flexural rigidity in the range of flange connection, as seen in Fig. 4(c), is ηE_iI_i.

2.2 Parameter calibration by test

Quasi static bending test was set up as Fig. 5(a). Lateral pull force was acted at top. A displacement sensor was set to measure the displacement at top. For each composite insulator, six strain gauges were placed on the surface of fiberglass composite tube.



(a) bending test set up (b) before test (c) after test

Fig. 5 Bending test of composite insulator

As seen in Fig. 5 (a), the bending moment, M, at position L_i under pull force F is

$$M=FL_i \tag{1}$$

The strain measured at position L_i is ε_i. Based on the stress and strain relationship, it has

$$E_i\varepsilon_i=MD/(2I_i) \tag{2}$$

in which E_i is elastic modulus of composite tube on which the strain is measured, I_i is the section inertia and D is the diameter. On the other hand, the force – displacement relation of cantilever column under lateral load gives

$$d=\sum_{i=1}^{4}\left(\int_{l_{1i}}\frac{M\bar{M}}{\eta E_i I_i}dl+\int_{l_{2i}}\frac{M\bar{M}}{E_i I_i}dl+\int_{l_{3i}}\frac{M\bar{M}}{\eta E_i I_i}dl\right) \tag{3}$$

In Eq. (3), l_{1i}, l_{2i} and l_{3i} are length in unit i, as shown in Fig. 4(c); M is the distribution of bending moment along the length of composite insulators under lateral lead F; $\bar{M}$ is the distribution of bending moment under unit lateral load.

Eqs. (1)-(3) can be used to solve elastic modulus of E_i for each insulator, and also factor η for the flexural rigidity at connection. Table 1 is the test result and solutions of E_i and η, from which a beam model of composite insulators can be built.

Table 1 Test results for flexural rigidity analysis

	Bending moment M, kN.m	Strain ε, με	Modulus, GPa	factor η
Unit 1	106.74	2115	26.9	F=11.9 kN d=0.288 m η=2.39
	95.80	1994		
	84.85	1728		
Unit 2	79.61	1606	26.3	
	68.43	1393		
	57.24	1047		
Unit 3	52.60	1180	20.2	
	41.06	1040		
	29.51	670		
Unit 4	25.82	568	19.5	
	13.69	330		
	1.55	35		

In the quasi static bending test, the composite insulator failed at a lateral force of 36.3 kN with sudden cracking of aluminum flange at bottom, as seen in Fig. 5(c). The force - displacement curve is plotted in Fig. 6. It can be observed that deterioration of stiffness happened when the lateral force F is 22kN, and when it reaches 36.3 kN, a sudden loss of load carrying capacity happened. The maximum bending moment at the bottom is 324 kN.m, and the stress at composite tube is 128 MPa. The fiberglass reinforced polymer has a common strength value over 200 MPa [14]. It implies that for the full scale specimen tested in this study, the strength of metal flange is a weak link. To further strengthen the composite insulator, it is important to increase the crack strength of metal flange, such as increasing the thickness of flange tube or adopting material with higher strength can be an option.

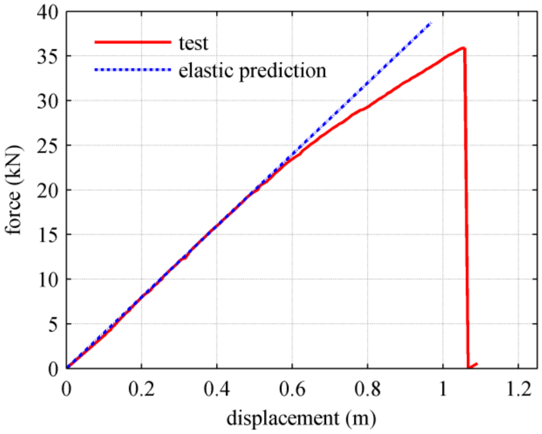


Fig.7 Force - displacement curve

Damping ratio is another important parameter in seismic performance analysis. An impact hammer test was carried out before bending test when the specimen was fixed at bottom and actuator had not fixed at the top. Acceleration transducers were set at end nodes of each composite insulator and hammer excitation was enforced at top. The modal shapes are showed in Fig. 8. The first model frequency is 1.66 Hz, with damping ratio of 2.52%. It should be noted that impact hammer test was carried out on composite insulator with mass much less than the final assembly, so the primary frequency of capacitor voltage transformer should be less than 1.66Hz. The frequency result can be used to check of results in bending test.

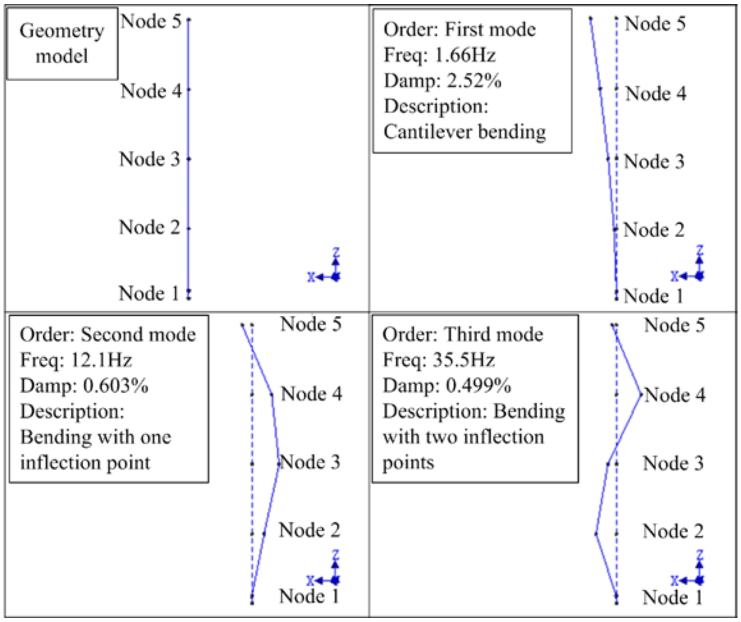


Fig. 8 Vibration modes of composite insulators (weight: 880kg) by impact hammer test

3 Seismic analysis and shaking table test validation

Based on the analytical model in Fig. 4(c) and test result on flexural rigidity in Table 1, numerical model of the 1 000 kV capacitor voltage transformer is built, as seen in Fig. 9(a). The elements in the model are defined with the stiffness parameter from bending test and mass parameter from the product specification. All of the mass in final assembly of the equipment has been added on the model, including the mass of grading rings, which are represented by node masses at corresponding position. Modal shapes from eigenvalue analysis are shown in Fig. 9 (b). The first three modal frequencies are 1.06 Hz, 6.93 Hz and 19.55 Hz.

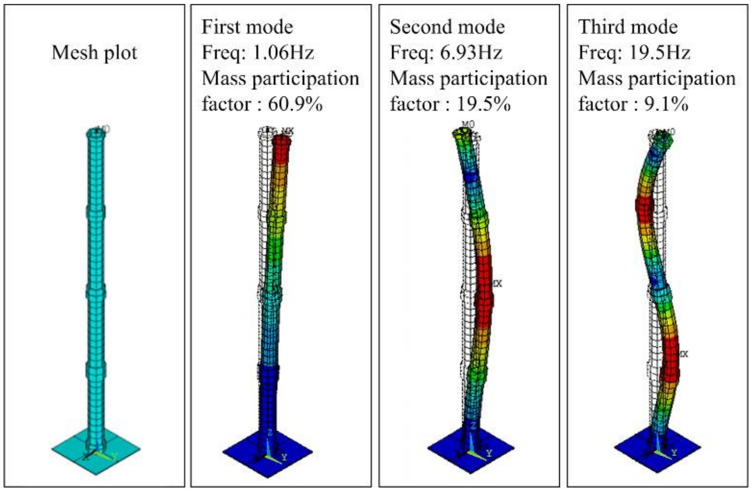


Fig. 9 Mesh plot of numerical model of 1 000 kV capacitor voltage transformer (weight 2800 kg) and modal shapes

In seismic analysis, a 0.3g artificial wave shown in Fig. 10 is chosen as input, which is also the input in shaking table test. As the analysis is assumed in elastic stage only, response spectrum method is adopted in seismic analysis. The analysis result is plotted in Fig. 11, in which maximum stress response at composite tube is 50.58 MPa happened at bottom of unit 4, maximum acceleration response is 14.18 m/s^2 happened at top of equipment and maximum displacement response at top is 304 mm.

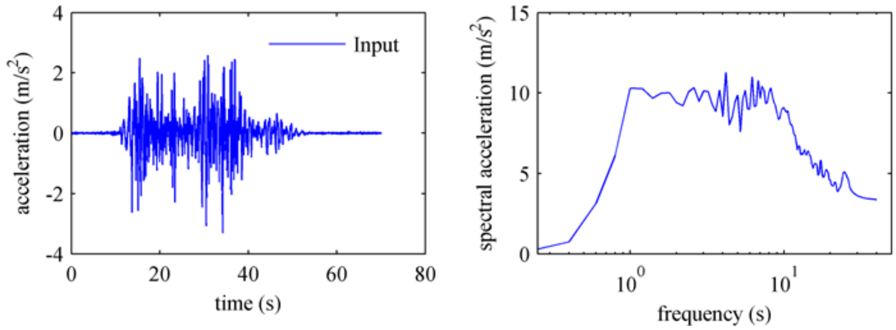


Fig. 10 Input acceleration wave adopted in seismic analysis and shaking table test

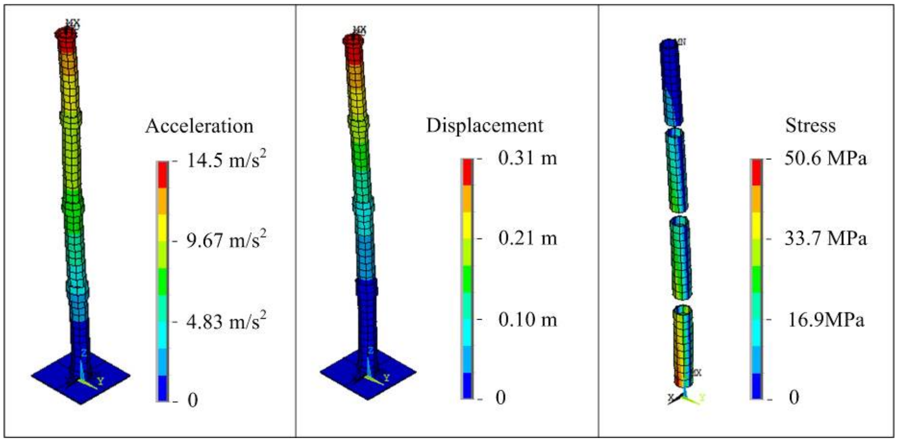


Fig.11 Seismic responses of acceleration (left), displacement (middle), and stress (right) Acceleration

In order to study seismic performance of the equipment under earthquake events and validate the numerical model, shaking table test of a full scale 1 000 kV capacitor voltage transformer was carried out. As shown in Fig. 12, the equipment was tested in its final assembly. Acceleration transducers were placed at top of each insulator unit, and strain gauges were set at surface of fiberglass tube at each unit. The input wave is shown in Fig. 10, which is a 0.3g level artificial wave. Time history seismic responses of 1 000 kV capacitor voltage transformer are plotted in Fig. 12. The fundamental frequency got from test is 1.02 Hz, maximum stress on fiberglass reinforced polymer tube is 45.3 MPa, and displacement at top is 344 mm. It is noted that under bending test, the flange of composite insulator cracked when the stress of fiberglass tube reached 128 MPa. It means that under 0.3g level input, the safety factor of the composite insulator is 2.8. A comparison between analysis results and shaking table test results is listed in Table 2.

Fig. 12 Shaking table test of 1 000 kV capacitor voltage transformer

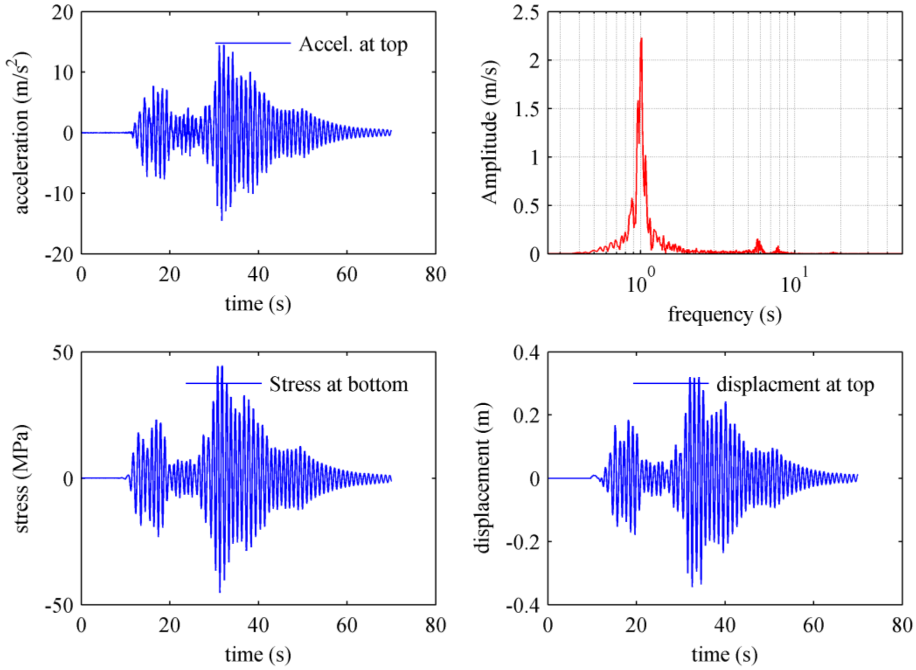


Fig 13 Response of 1 000 kV capacitor voltage transformer under shaking table test

Table 2 Comparison between analysis results and shaking table test results

Item		Test	Analysis	Difference
Predominant frequency		1.02	1.06	-3.92%
Stress at composite insulator, MPa	unit 1	12.76	12.53	1.84%
	unit 2	29.90	31.88	-6.62%
	unit 3	30.06	34.99	-16.40%
	unit 4	45.293	50.58	-11.67%
Acceleration at top of insulator, m/s^2	unit 1	14.53	14.19	2.40%
	unit 2	10.80	9.39	13.02%
	unit 3	8.15	7.46	8.42%
	unit 4	4.06	3.15	22.40%
Displacement at top of insulator, m	unit 1	0.34	0.30	11.72%
	unit 2	0.23	0.19	15.37%
	unit 3	0.12	0.096	18.62%
	unit 4	0.034	0.027	20.15%

It can be found that the numerical analysis has successfully predicted the maximum values of stress and acceleration response with a difference less than 5%, and the prediction of maximum displacement has a difference of 11.7%. The largest difference for all measured items is 22.40%. It shows that the numerical model build in this paper has a high overall accuracy in seismic response prediction.

In detailed design of substation, electrical equipment usually needs to be mounted on supporting structures and linked with nearby equipment [15]. These structures vary a lot in different substations. In this case, a numerical model is indispensable for the seismic safety check of equipment systems. The modelling procedure in this paper provides a useful tool for the seismic performance analysis of equipment with composite insulators.

4 Conclusions

Seismic performance and modeling method of electrical equipment made up of composite insulators are studied in this paper. By obtaining mass distribution of the equipment from product specification, carrying out bending test and impact hammer test to calibrate the stiffness and damping parameters of composite insulator, a procedure of numerical modelling of 1 000 kV composite capacitor voltage transformer is developed in this paper, and shaking table test is carried out as validation. The result shows that the modeling method can be used to predict the seismic response of the equipment with a satisfactory level of accuracy. It is also found in the bending test that the strength of composite insulator tested in this study is controlled by cracking strength of aluminum flange. Increasing the strength of metallic flange is important in further improvement of seismic performance of the composite insulator.

5. Acknowledgements

The research work in this paper is supported by the Scientific Research Program (GCB17201500063) of State Grid Corporation of China.

6. Copyrights

7 References

[1] Waser, R. (1992): *Ceramic Materials for Electronics; Processing, Properties, and Applications, 2. ed*. Marcel Dekker Inc., New York 1991

[2] Whittaker, A. S., Fenves, G. L., Gilani, A. S. J. (2007): Seismic evaluation and analysis of high-voltage substation disconnect switches. *Engineering Structures*, **29**(12), 3538-3549.

[3] Hwang, H. H. M., Huo, J. (1998): Seismic fragility analysis of electric substation equipment and structures. *Probabilistic Engineering Mechanics*, **13**(2), 107-116.

[4] Liu, Z. (2015): *Chapter 9 - UHV Substation and UHV AC Electrical Equipment Ultra-High Voltage Ac/dc Grids*. Boston: Academic Press.

[5] Ehsani, M., Borsi, H., Gockenbach, E., Morshedian, J., Bakhshandeh, G. R. (2004): An investigation of dynamic mechanical, thermal, and electrical properties of housing materials for outdoor polymeric insulators. *European Polymer Journal*, **40**(11), 2495-2503.

[6] Bonhte, P., Gmür, T., Botsis, J., Papailiou, K. O. (2004): Stress and damage analysis of composite-aluminium joints used in electrical insulators subject to traction and bending. *Composite Structures*, **64**(3-4), 359-367.

[7] Prenleloup, A., Gmür, T., Botsis, J., Papailiou, K. O., Obrist, K. (2009): Stress and failure analysis of crimped metal-composite joints used in electrical insulators subjected to bending. *Composites Part A: Applied Science and Manufacturing*, **40**(5), 644-652.

[8] Kumosa, M., Armentrout, D., Kumosa, L., Han, Y., Carpenter, S. H. (2002): Analyses of composite insulators with crimped end-fittings: part II-Suitable crimping conditions. *Composites Science and Technology*, **62**(9), 1209-1221.

[9] Kumosa, M., Han, Y., Kumosa, L. (2002): Analyses of composite insulators with crimped end-fittings: Part I-non linear finite element computations. Composites Science and Technology, **62**(9), 1191-1207.

[10] Roh, H., Oliveto, N. D., Reinhorn, A. M. (2012): Experimental test and modeling of hollow-core composite insulators. *Nonlinear Dynamics*, **69**(4), 1651-1663.

[11] Epackachi, S., Dolatshahi, K. M., Oliveto, N. D., Reinhorn, A. M. (2015): Mechanical behavior of electrical hollow composite post insulators: Experimental and analytical study. *Engineering Structures*, 93, 129-141.

[12] Anshel J. Schiff, Leon Kempner, Jr. IEEE 693 Seismic Qualification of Composite for Substation High-voltage Equipment. *13th World Conference on Earthquake Engineering*, Vancouver, B.C., Canada.

[13] Fahad, M. (2013): Seismic Evaluation and Qualification of Transformer Bushings. *The State University of New York at Buffalo*.

[14] K. O. Papailiou, F. Schmuck (2013): *Silicone Composite Insulators*. Springer-Verlag Berlin Heidelberg.

[15] IEEE Standard 693 (2005): *IEEE Recommended Practice for Seismic Design of Substations*.