Journal of Southeast University (English Edition) Vol. 41, No. 2, pp. 180-189 June 2025 ISSN 1003-7985

Effects of bolt joint loosening on the dynamic characteristics of electric angle steel transmission tower

CAI Yunzhu[1], XING Yujie[1], XIE Qiang[2], CHENG Xiaowu[1]

(1. College of Civil Engineering, Nanjing Tech University, Nanjing 211816, China; 2. College of Civil Engineering, Tongji University, Shanghai 200092, China)

Abstract: Transmission towers, serving as the support structure of transmission lines, are significant for the functionality of an electric transmission system. Bolt joint loosening is one of the critical factors that can affect the safety and stability of transmission towers. In this study, the effects of bolt joint loosening on the dynamic characteristics of a 220-kV angle steel transmission tower are the main topic of concern. First, the mechanical properties of typical joints subjected to different degrees of bolt loosening are studied by finite solid-element simulation, based on which a finite hybrid-element modeling method is developed for a tower structure suffering varying loose degrees in the joints. Taking a 220-kV angle steel transmission tower as the object, the influence of the position and degree of loosening on the tower's natural frequencies and mode shapes are simulated and discussed. The results demonstrate that the main-member splice joint and the main diagonal-horizontal member gusset plate joint account for the dominant impact on the dynamic characteristics of the tower. In addition, the dominant joint shifts from the main-member splice joint to the main diagonal-horizontal member gusset plate joint as the considered modal order increases. In the case of double joints loosening simultaneously, the loosening of nondominant joints has nonnegligible effects on the tower as well.

Key words: transmission tower; bolt joint; bolt loosening; dynamic characteristics

DOI: 10. 3969/j. issn. 1003-7985. 2025. 02. 007

The electric transmission network is a vital component of the power system, with transmission lines serving as essential infrastructure, which consists primarily of transmission towers and wires. Among these components, transmission towers function as crucial support structures for wires, and their safety and reliability significantly influence the stability of the power system. Transmission towers and wires exhibit significant flexibility, making them susceptible to fluctuating winds[1-4]. Consequently, the support tower structure sustains prolonged alternating loads, leading to the issue of bolt loosening in the joints, thereby influencing the mechanical behavior of the transmission tower in a detrimental manner[5].

Concerning the problem of bolt loosening, researchers combined the experimental study with the finite element simulation to explore the loosening mechanism and principles[6-7] and proposed the criteria to evaluate the loosening behavior of bolt connections that are forced to vibration[8]. The influencing factors for bolt loosening have been widely discussed, e. g. , load amplitude, phase difference, preload[9], thread clearance value, thread profile friction coefficients[10], initial preload, and shear displacement amplitude[11]. Regarding the bolt joints in a transmission tower, researchers employed experimental and numerical methods to study the performance of bolt joints with different preloads under the action of vertical load, tensile load, and vortex-induced vibration[12-14].

Dynamic characteristics, serving as critical indicators for evaluating and predicting structural responses, are significant in the structure design and safety assessment, thereby attracting wide attention[15-16]. Zhang et al. [17] studied the tower-line coupling effects on the frequencies and mode shapes of a tower through finite element simulation and experimental research, where they found that the first-order frequency increases with an increase in the total span length. Yin et al. [18] conducted data analysis of the transmission tower to extract and detect the modal parameters, where they determined that higher modes are generally more sensitive to damage. Zhu et al. [19] found that the first-order frequency tends to decrease with increasing tower height through data analysis obtained by the structural health monitoring system. Zhao et al. [20] investigated the effects of bolt joint loosening at local tower sections by numerical simulation, where they found that the loosening at local tower sections significantly affects high-order modes.

The bolt loosening theory and its applications have been extensively studied. Research studies on identifying and comparing the dynamic characteristics of transmission towers have attracted wide attention. Associating

Received 2024-06-10, **Revised** 2024-09-08.

Biography: Cai Yunzhu (1984—), female, doctor, lecturer, yunzhucai@ njtech. edu. cn.

Foundation items: The Youth Foundation Project of Jiangsu Province (No. BK20230337), the Natural Science Research of Jiangsu Higher Education Institutions of China (No. 22KJB560004), the National Natural Science Foundation of China (No. 52278523).

Citation: CAI Yunzhu, XING Yujie, XIE Qiang, et al. Effects of bolt joint loosening on the dynamic characteristics of electric angle steel transmission tower[J]. Journal of Southeast University (English Edition), 2025, 41(2): 180-189. DOI: 10. 3969/j. issn. 1003-7985. 2025. 02. 007.

the two aspects, the bolt joint loosening in a transmission tower makes a difference in its dynamic properties, and the influence is closely related to the varying loose degrees and positions. This paper takes the tower as a spatial member-joint system and focuses on analyzing the bolt joint loosening effects on tower dynamic properties, considering the changeable degrees and positions of the loose bolt joints. To this end, a finite hybrid-element modeling method is developed, and by the case design for joint loosening, the impacts referring to different loose degrees and positions are compared and discussed according to simulation results.

1 Finite Hybrid-Element Modeling for Tower Structure

Taking a typical 220-kV double-circuit angle steel transmission tower as an example, four typical bolt joints in the tower are concerned, and their mechanical behaviors with different loose degrees are simulated by finite solid-element modeling. On this basis, spring elements featured by the simulated displacement-load and rotation-moment curves are established and function as connectors for beam-element-based tower members, then achieving a finite hybrid-element model for the lattice tower structure.

1.1 Mechanical behavior of joints with loose bolts

According to the geometric features of the joints and the types of connected members, bolt joints in a typical angle steel transmission tower are classified into four types, as illustrated in Fig. 1. Joint *A* is an auxiliary-diagonal/main-member single-bolt joint. Joint *B* is a diagonal-main-member double-bolt joint. Joint *C* is a main-member splice joint. Joint *D* is a main diagonal-horizontal member gusset plate joint. The finite solid-element models of these joints are shown in Fig. 2. The corresponding mechanical curves of the four typical joints under varying degrees of bolt loosening are illustrated in Fig. 3. For the example 220-kV angle steel transmission tower (Fig. 4(b)), the connected members and connection details of the four regular joints are listed in Table 1.

For each typical joint, bolts and the connected members are simulated using solid elements, and the preloads of bolts are progressively weakened, corresponding to the different loose degrees. To simulate the preload of bolts, the fastening is implemented by introducing a cut surface or pretensioned section within the bolt and then applying a tensile load. Assuming that all the bolts involved in a joint have an identical loose degree, the preload of each bolt is initially taken to be 80 kN, according to the design standard, and decreases by 10 kN until reaching 30 kN, and then decreases by 5 kN until reaching 10 kN, totaling 9 loose degrees. Considering the varying loose degree, the mechanical properties of loose bolt joints characterized by the displacement−force and rotation-moment curves are obtained by the quasistatic incremental loading. The boundary constraints of each joint are summarized as follows: joint *A* undergoes the increasing axial tension on any auxiliary member with full constraints on remaining members; joint *B* experiences the increasing axial tension on any diagonal member with full constraints on remaining members; joint *C* undergoes the increasing axial tension to one end of the spliced main member with the other end fixed; joint *D* is subjected to the bending moment around the center, imposing full constraints on connected members. Fig. 3 illustrates the simulated displacement-force and rotation-moment curves of the four typical joints under varying degrees of bolt loosening. It is demonstrated that, with increasing bolt loosening, the sliding load of each joint significantly decreases. Joint *A* exhibits a two-stage behavior. Joint *B* shows a distinct sliding platform. Joint *C* shows multiple nonlinear stages with the loss of the preload force aggravating. Comparatively, the mechanical curve of joint *D* tends to be smooth.

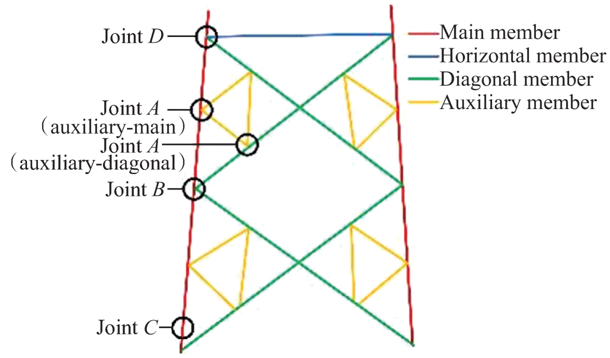

Fig. 1 Tower section diagram and typical joints

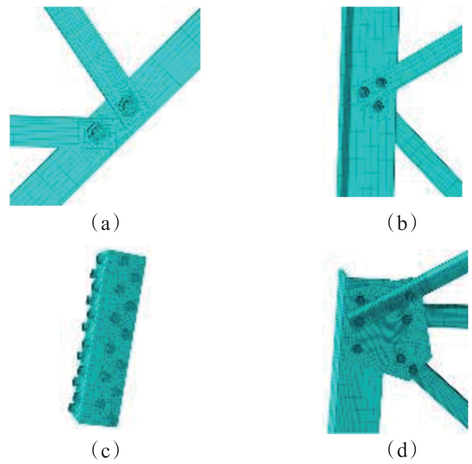

Fig. 2 Typical joint finite element models. (a) Joint *A*; (b) Joint *B*; (c) Joint *C*; (d) Joint *D*

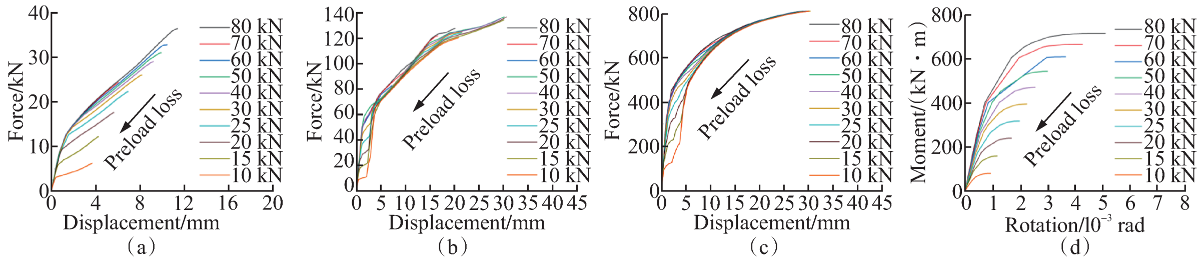

Fig. 3 Mechanical curves of typical joints under different bolt loose degrees. (a) Joint *A*; (b) Joint *B*; (c) Joint *C*; (d) Joint *D*

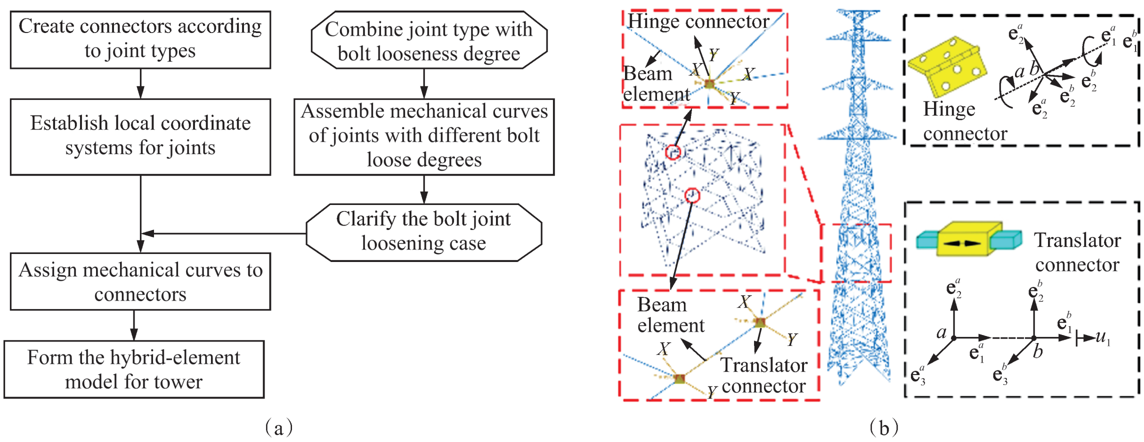

Fig. 4 Finite hybrid-element modeling for transmission tower. (a) Importing process of spring elements; (b) Joint simulation in a tower

Table 1 Parameters for typical bolt joints in the example tower

Material	Bolt type	Bolt hole spacing/ mm	Joint type	Bolt size/ (mm×mm)	Bolt number	Connected member size/ (mm×mm)	Gusset plate thickness/mm
Q345	HSFGB, Grade 8.8 (yield strength 640 MPa, tensile strength 800 MPa, preload 80 kN)	0.75	Joint *A*	M16×45	1	L40×4(A) L56×5(D)	
			Joint *B*	M16×45	2	L56×5(D) L125×10(M)	
			Joint *C*	M16×60	24	L125×10(M) L140×12(M)	
			Joint *D*	M16×35/40	7	L125×10(M) L56×5(D)/(H)	5

Note: A, D, M, and H represent auxiliary members, diagonal members, main members, and horizontal members, respectively; HSFGB is the high-strength friction-grip bolt.

1.2 Modeling of tower structure with loose bolt joints

Spring elements are utilized to simulate the joints that are subjected to the bolt preload loss, for which the mechanical properties are approximated by the curves generated according to the finite solid-element modeling of bolt joints with different loose degrees. Combining the spring-element-based joint model with the beam-element-based member model, a finite hybrid-element model for the tower structure experiencing the bolt joint loosening can be established according to the flowchart shown in Fig. 4 (a). Then, the translational single-degree-freedom translator connector is adopted to link the members involved in joints *A*, *B*, and *C*, and the rotational single-degree-freedom hinge connector is adopted to assemble the members involved in joint *D*, as shown in Fig. 4(b). The adopted translator and hinge connectors employ the spring elements to simulate their responses under loadings, whose mechanical behaviors are determined depending on their displacement-force and rotation-moment curves yielded by solid-element simulations of joints under different degrees of bolt loosening. Using the finite hybrid-element modeling, the example 220-kV angle steel tower depicted in Fig. 5 is established. To examine the availability of the model, a full-beam-element tower is established as well for comparison. Taking the case of bolt joints without looseness into account (i. e., the initial preload of 80 kN), the two models are subjected to the fluctuating load on the top of the tower, as shown in Fig. 6(a). The resultant vibration responses of the two models are plotted in Fig. 6

(b), demonstrating good accordance with each other. The agreement suggests that using the adopted connectors and defined spring elements to simulate bolt joints will not alter the dynamic performance of the tower. Then, the finite hybrid-element model of the tower is applied to compute the dynamic characteristics of transmission towers, addressing the bolt joint loosening with different degrees and varying positions.

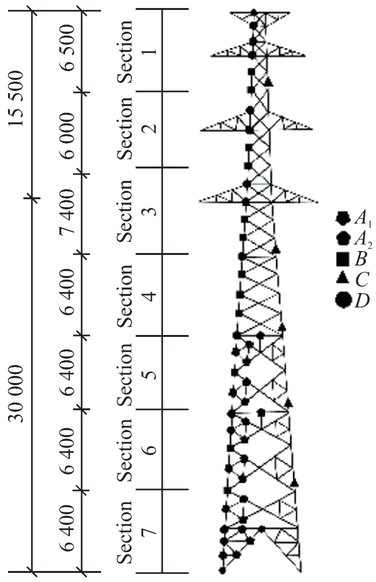

Fig. 5 Diagram of the example 220-kV angle steel tower (unit: mm)

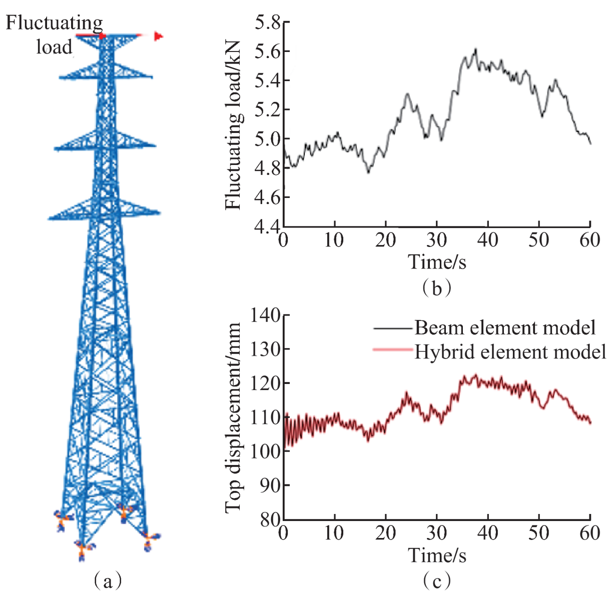

Fig. 6 Response comparison between the full-beam-element model and the hybrid-element model. (a) Tower model subjected to the fluctuating load; (b) Time history of fluctuating load; (c) Time histories of tower top displacement

2 Case Design for Bolt Joint Loosening in a Tower

The loose degree of bolt joints and the position of loose bolt joints are considered the two main factors affecting the dynamic characteristics of the tower in this study. For positioning the loose joints, the example tower structure is divided into seven sections, as shown in Fig. 5. To investigate the influence of the two factors, the bolt joints in a tower structure are classified into finite groups according to the tower section number and the joint type. Associating the four typical joints (i. e., joints *A*, *B*, *C*, and *D*) with the divided tower sections, joint groups denoted by *X*-*Y*, where *X* indicates the tower section number and *Y* denotes the joint type, are generated and listed in Table 2. To differentiate the auxiliary-main-member single-bolt joint from the auxiliary-diagonal-member single-bolt joint, joint *A* is further classified into type A1 and type A2, as depicted in Fig. 5 and Table 2.

Table 2 Bolt joints grouping

No.	Group name	No.	Group name	No.	Group name	No.	Group name	No.	Group name
1	1-D	5	4-C	9	5-B	13	6-A_2	17	7-A_1
2	2-D	6	4-D	10	5-C	14	6-B	18	7-A_2
3	3-D	7	5-A_1	11	5-D	15	6-C	19	7-D
4	4-B	8	5-A_2	12	6-A_1	16	6-D		

In the loosening case design, two scenarios are considered, i. e., the single joint group loosening and no more than two joint groups loosening. Relating the defined 9 loose degrees to the total 19 joint groups listed in Table 2, for the scenario where a single joint group loosens, the number of loosening cases is $1 + 19 \times 9 = 172$ (including nonlooseness); for the scenario where no more than two joint groups loosen, the number of loosening cases is $1 + 19 \times 9 + C_{19}^2 \times 9^2 = 14\ 023$ (including nonlooseness). Considering the loosening of single and double joint groups, the resultant effects on the tower dynamic characteristics are of concern in the following. The first five mode shapes of the tower are shown in Fig. 7.

3 Effects of the Joint Loosening on Tower Dynamic Characteristics

Utilizing the developed finite hybrid-element modeling method, the frequencies and shapes of the first five tower modes are simulated, involving the loosening cases of single and double joint groups. Frequencies and mode shapes, as well as their changes with the varying loose degrees and positions, are compared and discussed in the next section.

3.1 Single joint group loosening

Implementing the simulation on 172 cases of the single joint group loosening, Fig. 8 plots the frequencies of the first five modes of the tower separately, and their variations with the increasing looseness are figured out as well. In Fig. 8, it is demonstrated that with the looseness

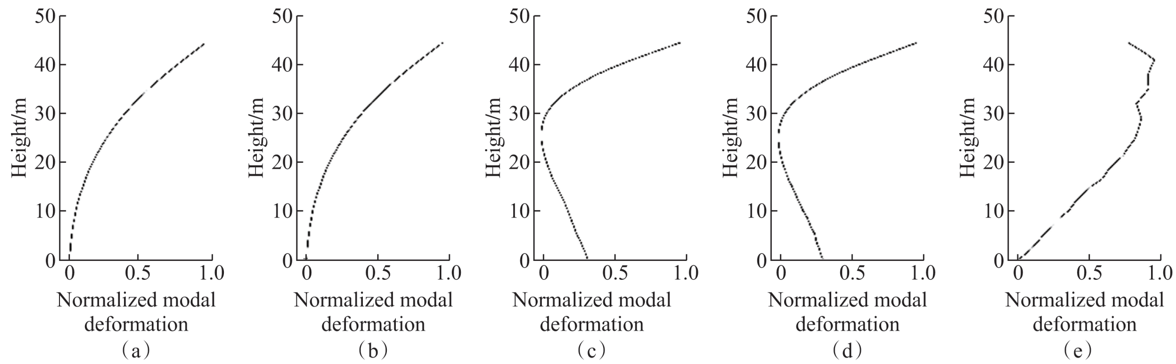

Fig. 7 First five mode shapes of transmission tower. (a) 1st mode; (b) 2nd mode; (c) 3rd mode; (d) 4th mode; (e) 5th mode

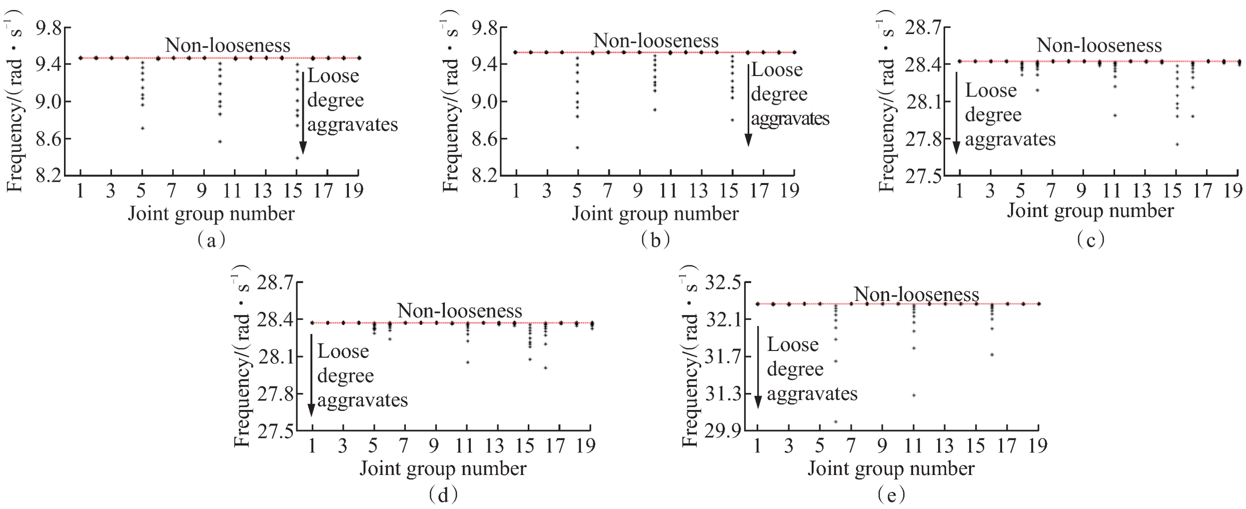

Fig. 8 Circular frequencies of the tower with single joint group loosened. (a) 1st mode; (b) 2nd mode; (c) 3rd mode; (d) 4th mode; (e) 5th mode

aggravating, circular frequencies of the first five modes show the tendency to decrease, and the decrease becomes more apparent with the increasing loose degree. In Figs. 8(a) and (b), the loosening of joint groups 5 (i. e., 4-C), 10 (i. e., 5-C), and 15 (i. e., 6-C) significantly affects the first-order bending frequencies that are transverse and longitudinal to the line. As for the second-order bending modes that are transverse and longitudinal to the line, it is shown in Figs. 8(c) and (d) that, except for the 4-C, 5-C, and 6-C joint groups, the loosening of joint groups 6 (i. e., 4-D), 11 (i. e., 5-D), and 16 (i. e., 6-D) also has critical effects on the circular frequencies. Fig. 8(e) illustrates that the three groups have a significant influence on the frequency of the torsion mode. It is found that the joint looseness happening in tower sections 4, 5, and 6 has the dominant effects on the first five modal frequencies of the tower, with the main-member splice joints notably influencing the first bending modes, the main-member splice joints and the main diagonal-horizontal member gusset plate joints impacting the second bending modes, and the main diagonal-horizontal member gusset plate joints playing a crucial role in the torsion mode.

Taking the original mode shapes as the reference, the joint-loosening-induced shape change is measured by the maximum difference of the normalized shape vector along the tower height. Fig. 9 shows the maximum differences of the first five mode shape vectors of the tower under the single loosening of 19 joint groups, including the designed 9 loose degrees. It reveals that similar to the tower frequency, the tower mode shape is influenced by the joint loosening, and the impact becomes significant with the loose degree increasing. Joint groups 5, 10, and 15 are the dominant joint groups affecting the first-order bending mode shapes. About the second-order bending modes, joint groups 6, 11, and 16 emerge as the added dominant-influencing joint groups. For the torsion mode, the dominant joint groups affecting the mode shape transfer from joint groups 5, 10, and 15 to 6, 11, and 16.

3.2 Double joint groups loosening

Considering the scenario of no more than double joints loosening with the total simulation cases of 14 023, the changes in frequencies of the first five modes of the tower due to varying loose degrees and positions are of particular concern. Taking the loose combination of arbitrary two joint groups into account, the maximum frequency changes induced by the combined looseness of double joint groups under 9 loose degrees are depicted in

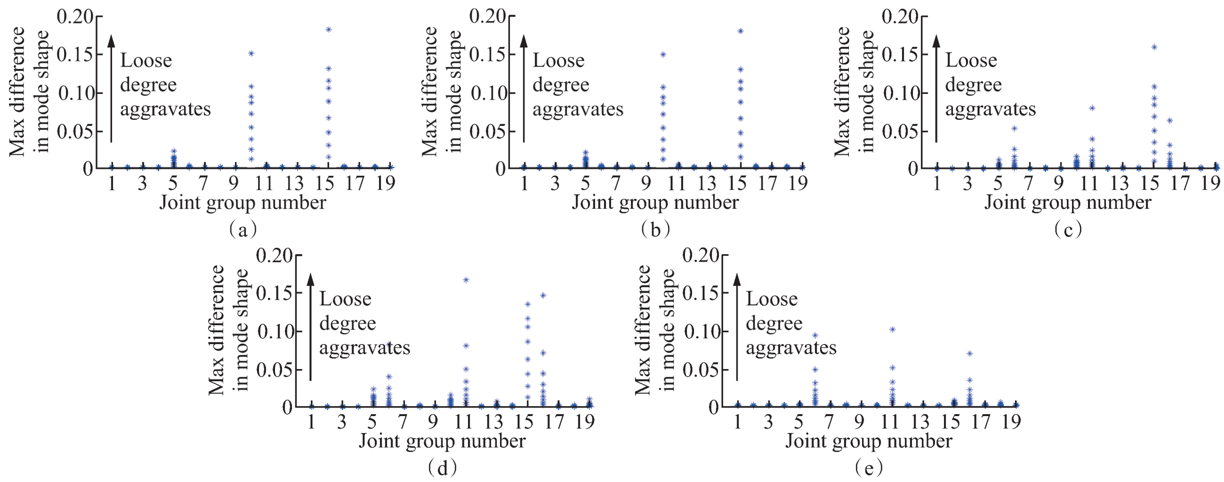

Fig. 9 Maximum differences in the normalized mode shapes of the tower with the single joint group loosened. (a) 1st mode; (b) 2nd mode; (c) 3rd mode; (d) 4th mode; (e) 5th mode

Fig. 10. Values measured by colors in Fig. 10 are the maximum difference between the original frequency and the loosening-resultant frequencies. Values for the diagonal elements denote the maximum frequency changes for the 9-degree looseness of single joint groups. The values highlighted by red circles in each subplot represent the maximum frequency changes observed among all values.

Concerning the first-order bending modes of the tower (Figs. 10 (a) and (b)), it is found that the combined looseness referring to any of joint groups 5, 10, and 15 has obvious effects on the frequency, and the pronounced frequency reductions occur when the three joint groups are pairwise loosened. The loose combination of joint groups 10 and 15 (i. e., the main-member splice joints in tower sections 5 and 6) results in the most significant frequency reduction for the transverse first-order bending mode and that of joint groups 5 and 15 (i. e., the main-member splice joints in tower sections 4 and 6) leads to the most critical frequency reduction for the longitudinal first-order bending mode. About the second-order bending modes (Figs. 10(c) and (d)), except from joint groups 5, 10, and 15, the loosening of joint groups 6, 11, and 16 makes a critical difference as well in the frequencies. For the torsion mode (Fig. 10(e)), the loose combination involving any of joint groups 6, 11, and 16 causes notable decreases in tower frequency, and the greatest decrease happens on the pairwise loosening of joint groups 6 and 11 (i. e., the gusset plate joints in tower sections 4 and 5).

Comparing diagonal and nondiagonal elements in Fig. 10 reveals that compared to the single joint group loosening, the combined loosening of double joint groups causes more apparent impacts on the tower. It is

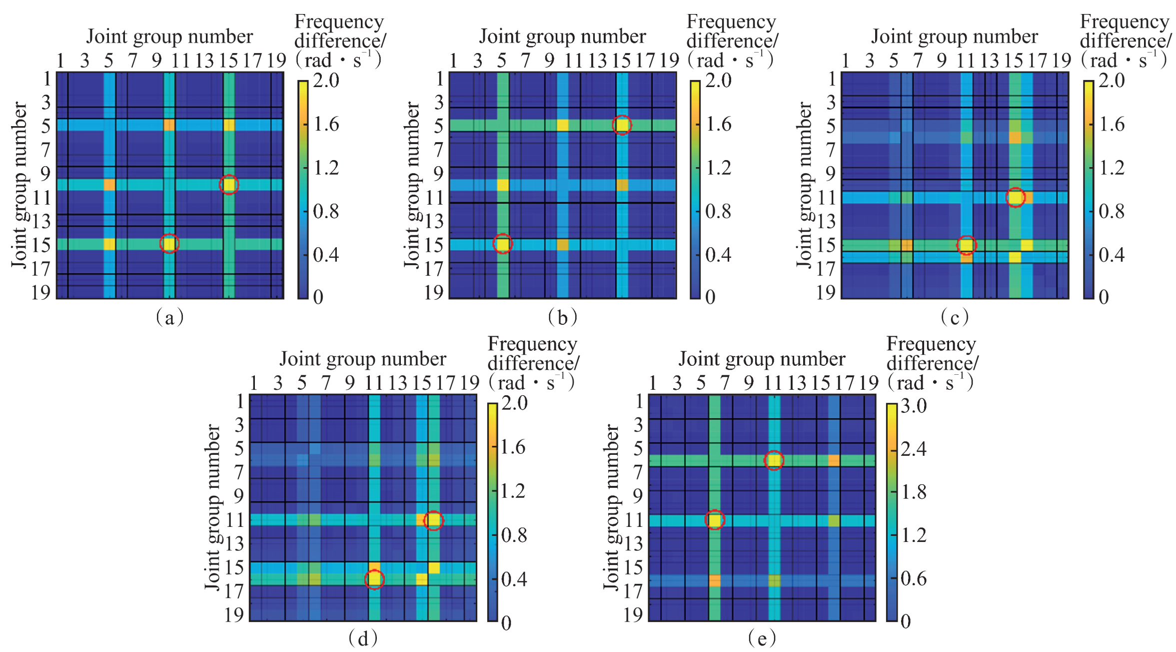

Fig. 10 Maximum circular frequency changes of the first five tower modes due to the combined loosening of double joint groups. (a) 1st mode; (b) 2nd mode; (c) 3rd mode; (d) 4th mode; (e) 5th mode

evident that the joint looseness happening in tower sections 4-6 will have significant effects on the tower frequency, and the main-member splice joints and the main diagonal-horizontal member gusset plate joints in these tower sections play the dominant roles in frequency reduction.

As for the mode shapes, taking the shape vectors without looseness as the reference, the maximum difference of the shape vector of the first five tower modes resulting from the combined loosening of double joint groups is calculated and depicted in Fig. 11. It shows the influence of the combined loosening of double joint groups exhibits the apparent difference for the first five tower modes. About the transverse first-order bending mode (Fig. 11(a)), the loose combination cases involving any of the dominant joint groups (i. e., joint groups 5, 10, and 15) cause significant impacts on the mode shapes, and same as the tower frequency, the pairwise loosening of joint groups 10 and 15 (i. e., the main-member splice joints in tower sections 5 and 6) results in the largest difference in the mode shape compared to other combinations. For the torsion mode (Fig. 11(e)), the impacts of loose combinations referring to any of joint groups 6, 11, and 16 take dominance, and the combined loosening of joint groups 6 and 11 (i. e., the gusset plate joints in tower sections 4 and 5) has the most crucial effect on the mode shape. Concerning the longitudinal first-order bending modes and the second-order bending modes of the tower (Figs. 11(b)-(d)), it is found that, compared with the frequency change shown in Fig. 10, the resultant differences in mode shape vectors exhibit the obvious nonuniformity, indicating the importance of considering the involvement of nondominant joint groups in loosening combinations.

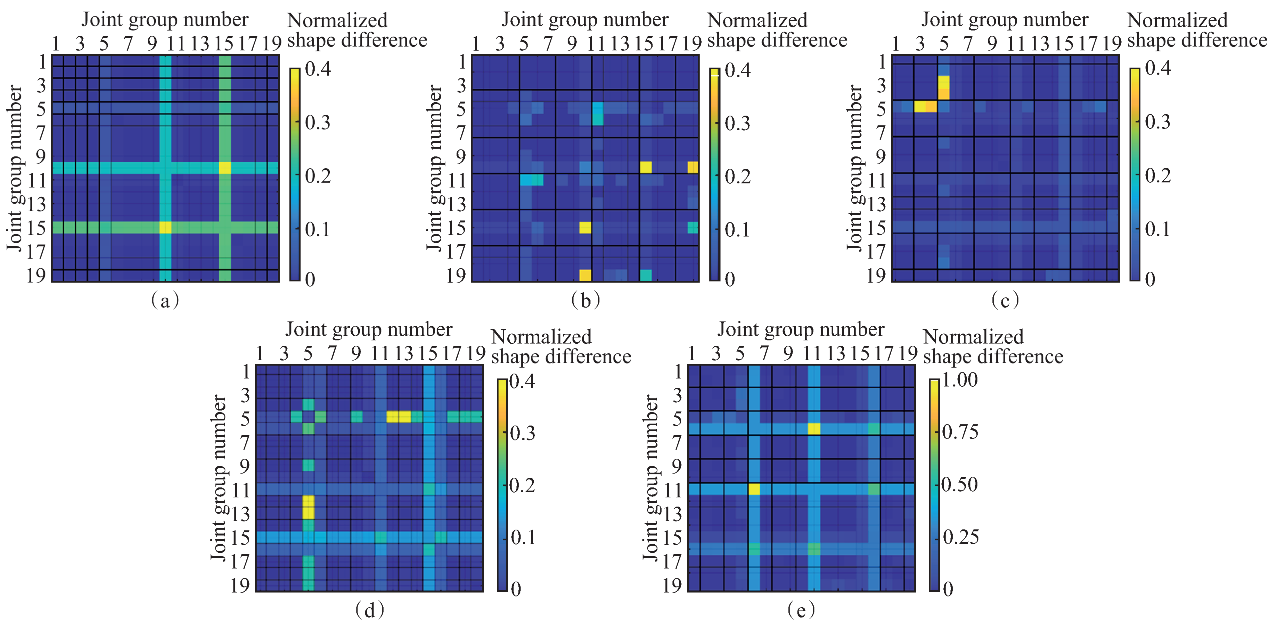

Fig. 11 Maximum difference of the first five mode shapes due to the combined loosening of double joint groups. (a) 1st mode; (b) 2nd mode; (c) 3rd mode; (d) 4th mode; (e) 5th mode

4 Comparison of the Joint Loosening Effects on Tower Modes

Comparing the joint loosening effects on the first five modes of the tower, the change rates of modal frequencies and shapes are examined for the five modes.

4.1 Modal frequency

Reduction rates of the circular frequency are calculated by taking the initial frequency value as the reference. Fig. 12 shows the average and standard deviation of frequency reduction rates induced by the looseness of a single joint group involving 9 loose degrees. The comparison among the five modes reveals that the effect of single joint loosening on the frequencies of first-order

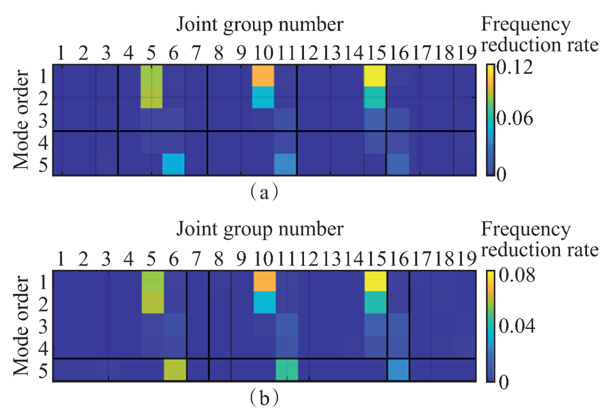

Fig. 12 Comparison of frequency reduction rates among the first five modes of the tower with single joint group loosened. (a) Average; (b) Standard deviation

bending modes is much more significant than on those of the second-order bending modes. For the torsion mode, the influence of single joint loosening becomes apparent again, with a noticeable transfer of dominant joint groups from groups 5, 10, and 15 to groups 6, 11, and 16. This means that the dominant-influencing joint changes from the main-member splice joint to the main diagonal-horizontal member gusset plate joint in tower sections 4-6.

Considering the double joint groups loosening, the dominant joint groups (i. e., groups 5, 10, 15, 6, 11, and 16) are pairwise combined, as listed in Table 3. Corresponding to the combination numbers, Fig. 13 depicts the average and standard deviation of the frequency reduction rate resulting from the double dominant joint groups loosening involving 9 loose degrees. Similar to the cases of single joint group loosening, the loosening of double dominant joint groups causes more pronounced impacts on the frequencies of the first-order bending modes than on those of the second-order bending modes. Notably, the frequency reduction rates under the loosening combinations of joint groups 7, 9, and 14 (i. e., the joint groups of 6-11, 6-16, and 11-16) are less significant for the first-order bending modes, whereas these become critical for the torsion mode. This means that the dominant-influencing combinations shift from the combined loosening of main-member splice joints to that of main diagonal-horizontal member gusset plate joints in tower sections 4-6.

Table 3 Combinations of double dominant joint groups

No.	Joint groups	No.	Joint groups	No.	Joint groups	No.	Joint groups	No.	Joint groups
1	5-6	4	5-15	7	6-11	10	10-11	13	11-15
2	5-10	5	5-16	8	6-15	11	10-15	14	11-16
3	5-11	6	6-10	9	6-16	12	10-16	15	15-16

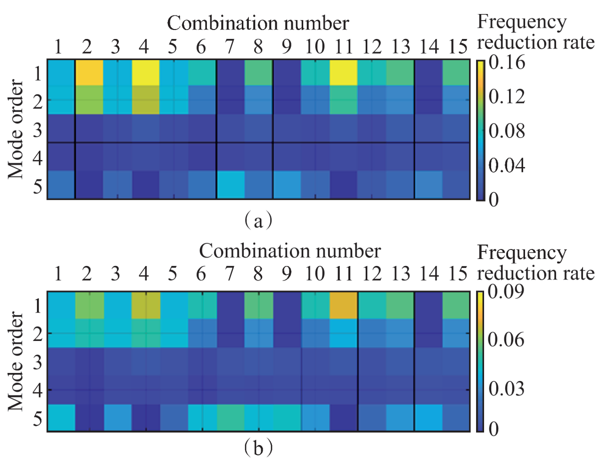

Fig. 13 Comparison of frequency reduction rates among the first five modes of the tower with double dominant joint groups loosened. (a) Average; (b) Standard deviation

4.2 Modal shapes

Taking the initial mode shape vector as the reference, the shape differences induced by bolt joint loosening are concerned, and the difference rates for the first five modes of the tower under the 9-degree loosening are calculated. Considering the looseness of a single joint group, Fig. 14 shows the average and standard deviation of the difference rates of mode shapes, referring to 19 loosening cases with 9 loose degrees involved. It demonstrates that the single joint group loosening has a remarkable influence on the third mode of the tower (i. e., the transverse second-order bending mode) in terms of the average and standard deviation. In addition, the loosening of joint group 5 (i. e., the main-member splice joints in tower section 4) exhibits the most significant impact.

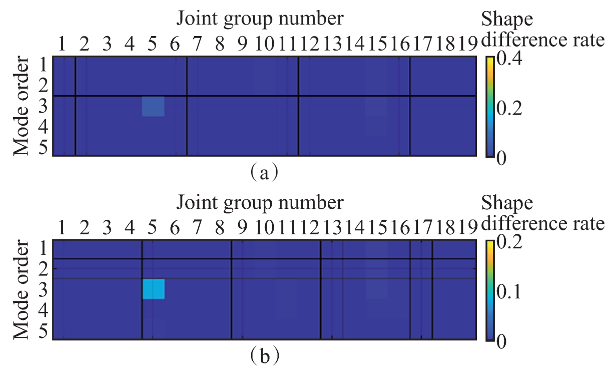

Fig. 14 Comparison of modal shape difference rates among the first five modes of the tower with single joint group loosened. (a) Average; (b) Standard deviation

For the looseness of double dominant joint groups, Fig. 15 plots the average and standard deviation of the difference rates of the first five modes under each combined loosening case. The results indicate that compared with the single joint group loosening, the double dominate joint group loosening significantly changes the mode shape of the second tower mode (i. e., the longitudinal first-order bending mode), with loose combination 10

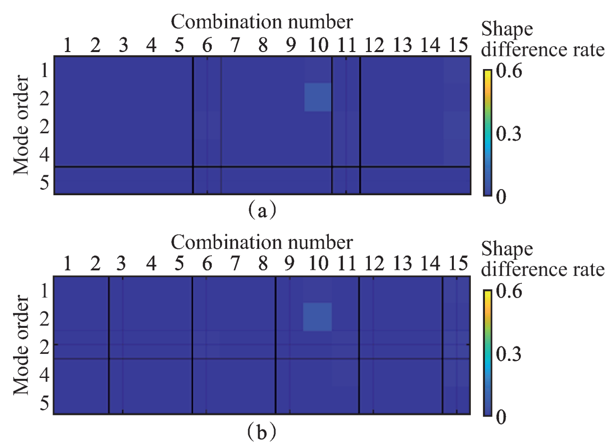

Fig. 15 Comparison of modal shape difference rates among the first five modes of the tower with double dominant joint groups loosened. (a) Average; (b) Standard deviation

(i. e., the combined loosening of joint groups 10 and 11) causing the greatest difference. This means that, among the five modes, the longitudinal first-order bending mode is most affected by the double dominant joint groups loosening, and the combined looseness of the main-member splice joints and the main-diagonal-horizontal member gusset plate joints in tower section 5 is the most influencing loosening case.

5 Conclusions

Bolt joint loosening is one of the critical factors that can affect the safety and stability of transmission towers. In this study, the effects of bolt joint loosening on the dynamic characteristics of a 220-kV angle steel transmission tower are the main topic of concern. Based on the results of this paper, the following conclusions have been drawn:

(1) The main-member splice joint and the main diagonal-horizontal member gusset plate joint in the middle sections of the tower body have the dominant influence on modal characteristics.

(2) Regarding the cases of single joint group loosening, the dominant-influencing joint changes from the main-member splice joint to the main diagonal-horizontal member gusset plate joint, as the concerned modes change from the first-order bending modes to the second-order bending modes and then to the torsion mode.

(3) Regarding the cases of double joint groups loosening, the combined loosening referring to any of the dominant joint groups causes significant changes in the tower frequency, and the pairwise loosening of two dominant joint groups exhibits the most pronounced impact. Concerning the differences in mode shapes, the influence of nondominant joint groups is critical for the tower subjected to no less than one joint group loosening.

(4) The mode shape difference induced by single joint group loosening is apparent for the transverse second-order bending, whereas under the double joint group loosening, the shape of the longitudinal first-order bending is most significantly changed.

References

[1] ZHANG Z Q, LI H N, LI S F, et al. Dynamic response analysis of transmission tower under wind-sand load induce[J]. Journal of Southeast University (Natural Science Edition), 2018, 48(3): 506-511. (in Chinese)

[2] CAI Y Z, WAN J W, XIE Q, et al. Numerical simulation on the typhoon-induced dynamic behavior of transmission tower-line system [J]. Wind and Structures, 2021, 33(4): 289-304.

[3] ZHANG Q, YE Z, CAI J G, et al. Wind-induced response of UHV long cantilever transmission tower and tower-line coupled system[J]. Journal of Southeast University (Natural Science Edition), 2019, 49(1): 1-8. (in Chinese)

[4] CAI Y Z, WAN J W. Wind-resistant capacity modeling for electric transmission line towers using Kriging surrogates and its application to structural fragility[J]. Applied Sciences-Basel, 2021, 11(11): 4714.

[5] LI J X, CHENG J P, ZHANG C, et al. Seismic response study of a steel lattice transmission tower considering the hysteresis characteristics of bolt joint slippage [J]. Engineering Structures, 2023, 281: 115754.

[6] FAN J F, LI H C, ZHANG Y Q, et al. Failure behaviour of bolted structures under cyclic transverse displacement[J]. Tribology International, 2023, 178: 108030.

[7] CHEN F, ZHANG J N, WANG C C, et al. Three-dimensional mechanical characteristics analysis of bolted joints and loosening mechanism[J]. Engineering Failure Analysis, 2024, 157: 107894.

[8] LI Z B, CHEN Y, SUN W C, et al. Study on self-loosening mechanism of bolted joint under rotational vibration [J]. Tribology International, 2021, 161: 107074.

[9] YANG L, YANG B, YANG G W, et al. Research on factors affecting competitive failure between loosening and fatigue of bolt under combined excitation[J]. Journal of Constructional Steel Research, 2022, 189: 107110.

[10] LIU X T, MI X, LIU J H, et al. Axial load distribution and self-loosening behavior of bolted joints subjected to torsional excitation [J]. Engineering Failure Analysis, 2021, 119: 104985.

[11] LIU J H, MI X, HU H M, et al. Loosening behaviour of threaded fasteners under cyclic shear displacement [J]. Wear, 2020, 460: 203453.

[12] AN L Q, WU J, JIANG W Q. Experimental and numerical study of the axial stiffness of bolted joints in steel lattice transmission tower legs[J]. Engineering Structures, 2019, 187: 490-503.

[13] XU J J, HE S Y, CAO X J, et al. Analytical and numerical analysis of angle steel joints for conductors in lattice transmission towers[J]. Case Studies in Construction Materials, 2022, 17: e01592.

[14] DENG H Z, JIANG Q, LI F, et al. Vortex-induced vibration tests of circular cylinders connected with typical joints in transmission towers[J]. Journal of Wind Engineering and Industrial Aerodynamics, 2011, 99(10): 1069-1078.

[15] YU C Y, ZHANG J R. Analysis on dynamic characteristics and wind-induced vibration response of transmission line systems[J]. Journal of Southeast University (Natural Science Edition), 2019, 49(1): 116-124. (in Chinese)

[16] SU Y H, ZHU Y M, ZHAO C, et al. Bayesian uncertainty quantification of modal parameters and RRF identification of transmission towers with limited measured vibration data [J]. Engineering Structures, 2024, 308: 118019.

[17] ZHANG Q, FU X, REN L, et al. Modal parameters of a transmission tower considering the coupling effects be-

tween the tower and lines[J]. Engineering Structures, 2020, 220: 110947.
[18] YIN T, LAM H F, CHOW H M, et al. Dynamic reduction-based structural damage detection of transmission tower utilizing ambient vibration data[J]. Engineering Structures, 2009, 31(9): 2009-2019.
[19] ZHU Y M, SUN Q, ZHAO C, et al. Operational modal analysis of two typical UHV transmission towers: A comparative study by fast Bayesian FFT method[J]. Engineering Structures, 2023, 277: 115425.
[20] ZHAO Y, XIAO Y, WANG H M, et al. Effect of bolt tightening force on the transmission tower modal parameters and a method for looseness identification[J]. Energy Reports, 2021, 7: 842-849.

螺栓节点松动对角钢输电塔动力特性影响规律研究

蔡云竹[1], 邢宇杰[1], 谢强[2], 程小武[1]
(1.南京工业大学土木工程学院,南京 211816; 2.同济大学土木工程学院,上海 200092)

摘要: 输电塔作为输电线的支撑结构,对输电线路的正常运行至关重要,而螺栓节点松动是影响输电塔安全稳定性的关键因素之一。本研究以220 kV角钢输电塔为研究对象,聚焦螺栓节点松动对角钢塔动力特性的影响。首先,通过实体单元有限元模拟,研究了典型节点在不同螺栓松动程度下的力学特性,并在此基础上开发了一种考虑节点松动程度变化的输电塔混合单元建模方法。然后,以220 kV角钢输电塔为研究对象,模拟并讨论了节点松动位置和程度对塔体固有频率和振型的影响及其规律。结果表明:主材拼接节点和主–斜–横材节点板节点对塔体动力特性具有主导影响。此外,随着所考查模态阶次的增长,主导节点从主材拼接节点逐渐转变为主–斜–横材节点板节点。当考虑双组节点同时松动时,非主导节点的松动对塔体的影响也不可忽视。

关键词: 输电塔;螺栓节点;节点松动;动力特性
中图分类号: TM75