Damage Location Identification for Bolt Looseness at Flange Joints of Leg Members in High-rise Steel Tubular Tower Structures

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Abstract

A number of high-rise latticed tower structures are made of steel tubular members. To facilitate the construction, the tower legs are constructed by connecting the steel tubular members with bolted flange joints. Under the wind load, the bolts of the flange joints may loosen; and this may endanger the safety of the tower if the bolt looseness and its locations cannot be detected and repaired timely. This paper proposes a new method for identifying the damage locations of bolt looseness of bolted flange joints at tower legs based on the abrupt changes of the structural responses of the towers to the wind load. The bolt looseness is reflected by the reduction of the bending rigidity of elements in the stiffness matrix of the beam element model which is equivalent to the refined solid finite element model of the flange joints. A vector composed of the standardized mean square deviations of the wind-induced longitudinal strain responses at flange joints in a damaged state of the tower related to those in its undamaged state is used as a damage index. It has been shown that the damage index is sensitive to the damage locations but independent of the wind load. Hence, the damage index can be used to identify the damage locations of the bolt looseness at the flange joints. Finally, the proposed method is applied to a latticed steel tubular tower, which shows that the proposed method can accurately identify the damage locations of bolt looseness.

Key words: damage identification, bolt looseness, flange joint, damage index, equivalent method

1 Introduction

High-rise latticed tower structures, such as transmission towers and television towers, are often made of steel tubular members. To facilitate the construction, the tower legs are usually constructed by connecting the steel tubular members with bolted flange joints as shown in Fig. 1.

Under the wind load, the bolts at flange joints of a steel tubular tower may loosen and the bolt looseness often occurs at the joints of the tower legs, which may reduce the wind-resistant capability of the tower, increase the wind-induced displacement responses and affect the serviceability of the tower. When the number of loosened bolts is sufficiently large, it may endanger the safety of the tower-structure and even lead to its collapse if the bolt looseness and the corresponding locations cannot be detected and repaired timely. Therefore, it is essential to detect the locations of loosened bolts timely and accurately, the repair can be carried out to ensure the safety of the tower. However, detection of the accurate locations of loosened bolts during the service life of structure is quite difficult.

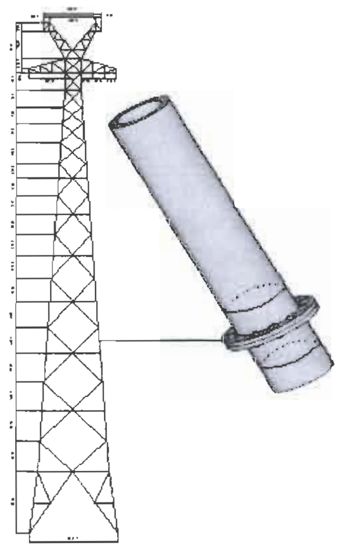

Fig. 1. Schematic diagram of flange

The studies of damage detection about bolt looseness have been focused mainly on mechanical and aeronautical engineering fields. Ding and Jung(1),(2) utilized the vibration characteristics of bolts under external loads to prevent bolts from loosening. Ayres et al(3) diagnosed the specific locations of bolt looseness using the acceleration response near the bolts. Kuo and Jayasuriya(4) used transfer functions to determine the extent of joint loosening in automobile vehicle frames with high mileages. Caccese et al.(5) identified the locations of loosened bolts through the change of a damage index derived from the transfer function. Zubaydi et al.(6) investigated the damage detection of composite ship hulls using neural networks. Masayuki(7) proposed a new method for the bolt loosening detection by using a smart piezoelectric washer with a sub-space state space identification algorithm. Lew and Juang(8) adopted a passive control technique in conjunction with piezoelectric materials to detect the locations of damages. Dansoh et al.(9)carried out an experimental investigation to use the change of compressive and tensile properties of butt-jointed lamination to determine the looseness on the joints. Park et al.(10)studied wireless impedance sensors for structural damage identification and sensor self-diagnosis. Timothy et al.(11) used smart sensor arrays for distributed structural health monitoring and bolt looseness damage diagnosis.

These methods can be classified into three categories. The first category of methods detects the locations of bolt looseness by discriminating the change of the structural responses to the specifically applied excitations; the second category of methods diagnoses the damaged locations of bolt looseness by measuring the impedance characteristics of the structure, while the third category of methods uses sensors to measure the change of the retightening force in bolted joints to detect the damage locations of bolt looseness. However, all these methods are developed for the application in the mechanical and aeronautical engineering fields and are difficult to be used for detecting the locations of bolt looseness of latticed steel tubular towers. Because the towers are quite high (up to 300 meters) and, particularly, the number of bolts is often very large, it is infeasible to apply the required excitations and to install a large number of the specific instruments and so the first and second categories of methods are not practical for high-rise steel tubular tower structures. The third category of methods requires installation of sensors. For the steel tubular towers, a large number of sensors need to be installed, which is very costly and unacceptable, especially when compared with the cost of the steel tubular towers themselves. Therefore, it is much needed to develop a new method for detecting the bolt looseness and the corresponding locations of steel tubular towers.

The purpose of this paper is to develop a new method for identifying the damage locations of bolt looseness at flange joints of steel latticed tower legs. In the paper, the bolt looseness is reflected by the reduction of the bending rigidity of the equivalent beam element, whose stiffness matrix is obtained by comparing with a refined solid finite element (FE) model of the flange joint. A vector composed of the standardized mean square deviation of the wind-induced longitudinal strain responses at flange joints of the latticed tower in the tower leg directions under the damaged state of the tower compared to its undamaged state is proposed as a damage index. The damage index is to be shown to be sensitive to the damage locations but independent of wind load. Hence, the damage index vector can be used for damage location identification for bolt looseness at flange joints by detecting its abrupt change information. Lastly, the method proposed in this paper is applied to a damaged tower to show the accuracy and feasibility.

2 Theories and Method

2.1 Damage index

2.1.1 Equivalent methods of bolt looseness

In order to analyze the effects of bolt looseness on the structural behavior of the steel tubular tower, a simplified equivalent beam element model for the flange joint, which can produce results equivalent to those obtained from a refined solid FE model, is formulated. In the simplified model, bolt looseness is determined by the reduction of the equivalent stiffness of the beam element, and the bending rigidity of the stiffness matrix of the beam element model is used as an adjusting parameter. The details of the process are as follows.

(1) A refined solid finite element model of the flange joints (considering various kinds of bolt looseness) and a corresponding simplified equivalent beam element model are established as shown in Fig. 2.

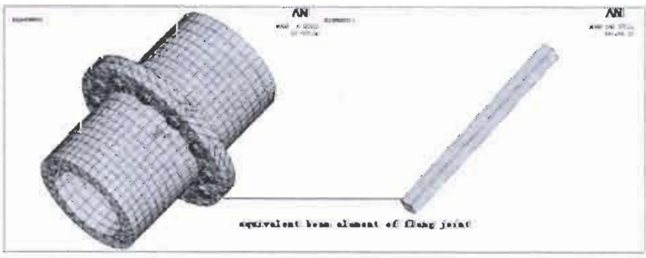

Fig. 2. Refined solid FE model and equivalent beam element model for flange joint

(2) The stiffness of the refined solid model of the flange joint is determined by moving a unit displacement of the member end in the corresponding direction of the beam element and taking the reactive forces of the corresponding restraint as the stiffness. The stiffness matrix of the refined solid model of the flange joint can then be used for the equivalent beam element model.

(3) Because the bolt looseness at the flange joints would influence the lateral, torsional and bending stiffnesses, it is necessary to investigate the effect of the bolt looseness on all these stiffnesses. A flange joint is used to illustrate this. The dimensions of the flange joint with 12 bolts are shown in Fig.3 and the effects of the bolt looseness on the stiffnesses are shown in Tables 1:

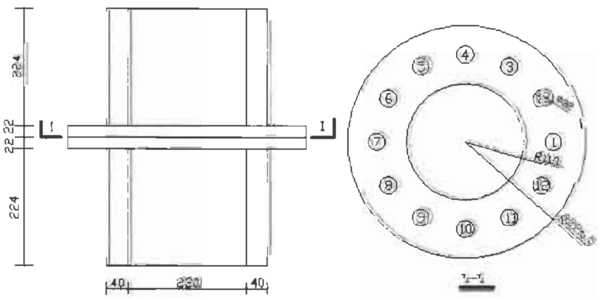

Fig. 3. The geometric properties of the flange joint

Table 1 The effects of bolt looseness for the element of the stiffness matrix

Equivalent beam element model	lateral stiffness EI_Z $(N\cdot m^2)$	lateral stiffness EI_Y $(N\cdot m^2)$	torsional stiffness GI_X $(N\cdot m^2)$	bending stiffness EI_Y $(N\cdot m^2)$	bending stiffness EI_Z $(N\cdot m^2)$
Undamaged state	20498	20646	39870	21128	21093
Damaged state Location:1	19268	19658	39291	20287	20870
Damaged state Location:1 7	17857	18259	38258	19148	20637
Damaged state Location:1 5 9	16493	16714	36649	18280	20543
Damaged state Location:1 4 7 10	14996	15039	34280	17611	20506
Damaged state Location:1.2.3.4.5	13706	13489	31285	16854	20472
Damaged state Location:1.3.5.7.9.11	11995	11433	27802	16300	20381

It can be seen from Table 1 that the bolt looseness have great effects on the bending stiffness. Because the bending stiffness can be derived from the longitudinal strains at the outside of flange joints (Fig.4), the longitudinal strains at the outside of flange joints can be used as equivalent variables to characterize the bolt looseness of the flange joints.

2.1.2 The mean square deviation of wind-induced longitudinal strain responses

To identify the bolt looseness locations at bolted flange joints of tower legs based on the structural responses of a tower to the wind load, it necessary to find those responses which are sensitive to the bolt looseness of flange joints.

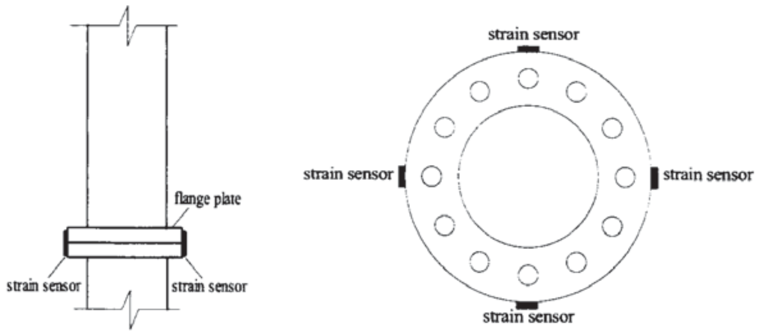

Fig. 4. Locations of strain sensors at a flange joint

It is known that the wind-induced responses at the outside of flange joints are most sensitive to the bolt looseness of flange joints. Hence, fluctuating wind longitudinal strain responses at the outside of flange joints are used for detection of bolt looseness of flange joints and their mean value and mean square deviation are defined as

$$\begin{aligned} \tilde{\varepsilon}_i(z_i) &= \varepsilon_i(z_i) - \bar{\varepsilon}_i(\varepsilon_i) \\ \sigma_{\varepsilon_i}^2 &= D(\tilde{\varepsilon}_i) \end{aligned} \tag{1}$$

where ε_i is the measured data of longitudinal strain responses; $\bar{\varepsilon}_i$ is the statistics mean of time history of longitudinal strain responses; $\tilde{\varepsilon}_i$ is the fluctuating strain responses; σ_{ε_i} is the mean square deviation of fluctuating strain responses.

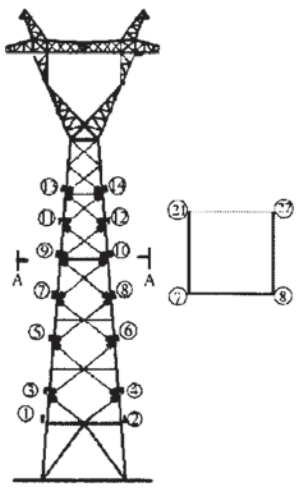

Fig. 5. Transmission tower

In order to find the sensitivity of the mean square deviation of the wind-induced longitudinal strain responses to the bolt looseness, the simulation of wind-induced structural responses (the mean wind pressure is $\overline{w}_{10} = 0.3kN / m^2$) of the undamaged state of a steel tubular tower (Fig.5) was compared with that of the corresponding damaged state due to bolt looseness by using the commercial FE software ANSYS. The tower models are established by BEAM44 element, and the damaged state of the tower has three loosened bolts in the 6th and 12th flange joints (there are twelve bolts in a flange joint) respectively. The bolt looseness is determined by adjusting the bending stiffness of the beam element model. The mean square deviation σ_{ε_i} and the maximum wind-induced longitudinal strain responses $\varepsilon_{i\max}$ were obtained as shown in Table 2.

Table 2. Longitudinal strain responses at flange joints in damaged and undamaged states

Flange joint (με)		1	6	8	10	12	13
Undamaged state	$\sigma^u_{\varepsilon_i}$	23.792	21.390	21.384	18.516	18.512	16.318
	$\varepsilon^u_{i\max}$	63.7	60.62	54.3	55.7	45.6	39.33
Damaged state	$\sigma^D_{\varepsilon_i}$	23.788	25.484	21.388	18.52	22.055	16.323
	$\varepsilon^D_{i\max}$	63.7	72.22	54.3	55.7	54.4	39.33
Difference	σ_{ε_i}	0	4.1	0	0	3.5	0
	$\varepsilon_{i\max}$	0	11.6	0	0	8.8	0

It can be seen from Table 2 that in the damaged state, the changes of σ_{ε_i} and $\varepsilon_{i\max}$ at the 6th and 12th flange joints are significant compared with the undamaged state, and that there are no changes of σ_{ε_i} and $\varepsilon_{i\max}$ at other flange joints. The results indicate that the longitudinal strain responses of the flange joints change only at the damaged flange joints. When the mean wind pressure is 0.3kN/m2 at the standard height of 10 meters, the maximum difference in longitudinal strain responses at flange joints between the damage and undamaged states can reach 8.8 to 11.6 $\mu\varepsilon$, and their mean square deviation can reach 3.5 to 4.1 $\mu\varepsilon$ (The sensitivity of fiber Bragg grating strain sensor is 1.0 to 2.0 $\mu\varepsilon$). This shows that the longitudinal strain responses at flange joints are very sensitive to the damages due to bolt looseness.

2.1.3 Linear relationship of mean square deviation of longitudinal strain responses with wind load

Because the mean square deviation of wind-induced longitudinal strain responses is related to the wind load, it should be standardized to exclude the effects of the wind load and the standardized mean square deviation can then be used to form a damage index for detecting the bolt looseness of flange joints.

According to the Davenport wind spectrum, if a tower structure is simplified into a lumped mass model with the lumped mass at the node levels, the mean square deviation of wind-induced longitudinal strain responses of the i-th flange joint can be expressed as [12] :

$$\sigma_{\varepsilon_i} = \left[\sum_{j=1}^{N} (\mathrm{B}_{ij}^{*})^2 \frac{1}{(\mathrm{M}_j^{*})^2} \int_{-\infty}^{\infty} \left| \mathrm{H}_j^{*}(in) \right|^2 \{\Phi\}_j^T \left[S_p(n) \right] \{\Phi\}_j \, dn \right]^{1/2} \tag{2}$$

where the element of the contribution matrix B_{ij}^{*} presents the contribution of the j-th horizontal displacement mode to the longitudinal strain response of the i-th flange joint, M_j^{*} is the generalized mass corresponding to the j-th horizontal displacement mode, $\{\Phi\}_j$ is the j-th horizontal displacement mode, $[S_p(n)]$ is the cross power spectral density functions of the fluctuating wind load vector.

Because the height of the steel tower is much greater than its depth and width, the correlation of the fluctuating wind load in the directions of its depth and width can be ignored, the cross-power spectral density functions of the fluctuating wind load vector in the vertical direction can be obtained as [13]:

$$\left[S_p(\omega) \right] = \left[S_p \right] S_f(n) \tag{3}$$

where $S_f(n) = \dfrac{2x^2}{3n(1+x^2)^{4/3}}$ is the standardized Davenport wind spectrum, $\left[S_p \right]$ is the coefficient matrix with the element $S_{p_{ij}}$, and $S_{p_{ij}}$ can be defined as

$$S_{p_{ij}} = \rho_{ij} \overline{p}_i \overline{p}_j \tag{4}$$

where ρ_{ij} is the vertical coherence function of the wind load, $\overline{p}_i \overline{p}_j$ is the wind load factor of the i-th and j-th node layer, and p_i can be defined as

$$\overline{p}_i(z_i) = \sqrt{24K} \overline{w}_{z_i} \frac{\overline{v}_{10}}{\overline{v}_{z_i}} \cdot \mu_D(z_i) \Delta A(z_i) \tag{5}$$

$$\overline{w}_{z_i} = \left[\left(\frac{z_i}{H_T} \right)^{2\alpha} \cdot 35^{0.32} \right] \overline{w}_{10} \tag{6}$$

Where K is the coefficient in the Davenport wind spectrum related to the ground roughness, $\overline{w}_{z_i}$ is the mean wind pressure at the height of Z_i, $\overline{v_{z_i}}$ is the mean wind speed at the height of Z_i, $\overline{v}_{10}$ is the mean wind speed at the height of 10m, $\mu_D(z_i)$ is the flow resistance coefficient at the height of Z_i, $\Delta \mathrm{A}(z_i)$ is the area of the windward side , $\mathrm{H_T}$ is the height of the gradient wind, α is the roughness length, and $\overline{w}_{10}$ is the mean wind pressure at the standardized height.

By assuming $\left[S_p \right] = \left[\overline{S}_p \right] \cdot \overline{w}_{10}$, then $\left[\overline{S}_p \right]$ is relevant to the structural parameters of the tower and depends on the wind environment, but independent of the wind load. Eq.(2) can then be rewritten as:

$$\sigma_{\varepsilon_i} = \overline{w}_{10} \cdot \xi_i \tag{7}$$

$$\xi_i = \left[\sum_{j=1}^{N} (\mathrm{B}_{ij}^{*})^2 \frac{\{\Phi\}_j^T \left[\overline{S}_p \right] \{\Phi\}_j}{(\mathrm{M}_i^{*})^2} \int_{-\infty}^{\infty} \left| \mathrm{H}_j^{*}(in) \right|^2 S_f(n) dn \right]^{1/2} \tag{8}$$

It can be seen from Eq. (8) that ξ_i is related only to the structural parameters associated with the damage, which shows that the relationship between the mean square deviation of wind-induced longitudinal strain responses in the tower leg direction and wind load is linear.

2.1.4 Damage index for identifying bolt looseness in flange joints

For the mean wind pressure $\overline{w}_{10}$ at 10 meters height in every ten minutes is measurable, the damage index vector can be formed as

$$\{E\} = \left[\Delta\sigma_1 ......\Delta\sigma_i ......\Delta\sigma_\ell\right]^T \tag{9}$$

In which $\Delta\sigma_i$ is the standardized damage index of the wind-induced longitudinal strain responses at flange joints in the i-th node given by

$$\Delta\sigma_i = \frac{\left(\sigma_{\varepsilon_i}^D / \overline{w}_{10}^D - \sigma_{\varepsilon_i}^u / \overline{w}_{10}^u\right)}{\sigma_{\varepsilon_i}^u / \overline{w}_{10}^u} = \frac{\xi_i^D - \xi_i^u}{\xi_i^u} \quad (i = 1, ..., l) \tag{10}$$

where $\sigma_{\varepsilon_i}^D$ is the mean square deviation of the wind-induced longitudinal strain responses at the i-th node in the damaged state, $\sigma_{\varepsilon_i}^u$ is the mean square deviation of the wind-induced longitudinal strain response of the i-th node in the undamaged state, ℓ is the level number of the tower; $\overline{w}_{10}^u$ is the mean wind pressure of the undamaged state at the standardized height and at the time of the field measurement, and $\overline{w}_{10}^D$ is the mean wind pressure at the standardized height and at the time of the field measurement in the damaged state.

From Eq. (10), the standardized $\Delta\sigma_i$ is independent of the wind load. Since the mean square deviation σ_{ε_i} is sensitive to the bolt looseness, ξ_i^D is very different from ξ_i^u when the joint of the i-th node level is damaged, and so $\Delta\sigma_i$ is also sensitive to the bolt looseness. Because the mean square deviation for the damaged joints is localized, when the k-th bolt was loosened, $\Delta\sigma_k \neq 0$ and $\Delta\sigma_{j\neq k} \approx 0$ in the vector $\{E\}$. The characteristics of the vector $\{E\}$ can then be summarized as follows:

(1) It is independent of the wind load;

(2) It is sensitive to the bolt looseness at flange joints; and

(3) The elements of the vector is localized, i.e. the elements corresponding to the flange joints with bolt loosening damages demonstrate changes, while changes of the elements corresponding to the flange joints without bolt loosening damages are close to zero.

2.2 Method for identifying locations of bolt looseness at the flange joints

From the previous discussion, the elements of the damage index $\{E\}$ corresponding to the damaged flange joints have an abrupt change. The location of the abrupt change is just the location of the damaged flange joint. A threshold can be defined according to the situation of a steel tubular tower structure. A joint is considered to be damaged when the value of its damage index exceeds the threshold. The steps for identification of damage locations of bolt looseness at flange joints can be summarize as:

(1) Installation of fiber Bragg grating strain sensors at the outside of the flange joints of tower legs as shown in Fig.4;

(2) Measurement of the wind-induced longitudinal strain response at flange joints in the undamaged state, and calculation of the mean square deviation for the undamaged state;

(3) Real-time measurements of the mean square deviation for the wind-induced longitudinal strain response at flange joints and formation of the damage index vector $\{E\}$;

(4) Detection of the abrupt change of the elements of the damage index vector $\{E\}$, and determination of the damaged flanged joints.

3 Numerical Simulations

3.1 General

The proposed method is applied to the latticed transmission tower shown in Fig.4. The geometric and material properties of the cross-section of the four legs of the tower are shown in Table.3, where 1 and 2 represent the leg cross-section of the bottom and top four segments respectively.

Table.3. Cross-section parameters of main rods

main rods	*R* (*m*)	*t* (*m*)	*A* (m^2)	*I* (m^4)	*E* (*pa*)	*EI* ($pa.m^4$)	*EA* ($p.m^2$)	ρ (kg/m^3)
1	0.15	0.04	3.06e-2	2.516e-4	2.06e11	5.18e7	6.30e9	7850
2	0.15	0.02	1.83e-2	1.758e-4	2.06e11	3.62e7	3.77e9	7850

3.2 Calculation of damage coefficient

In order to verify the effectiveness of the proposed method for detecting damage locations, the finite element models in the damaged state and undamaged state of the latticed transmission tower are established. For the damaged state of the transmission tower, four symmetric loosened bolts are simulated at each flange joint of joints 6, 12, 19 and 26 (Fig. 6). The blot looseness of each flange joint occurs at the positions 1、4、7 and 10 in its plane as shown in Fig.6.

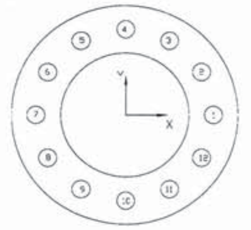

Fig. 6. Plane of a flange joint

A refined solid FE model of flange joint is simulated with SOLID73 element of the commercial finite element software ANSYS. The high strength bolts of Grade 8.8 M30 with the yield point at 990 N/mm2 is used, and its designed pre-tightening force is 250KN. The main steel tubes are made of 16Mn steel with the yield point at 345 N/mm and an anti-slip coefficient 0.4.

In order to simulate the real stress distribution, the contact analysis of the bolt head and flange are considered. The contact analysis models are simulated by TARGET170 element and CONTA174 element of ANSYS. The pretension area is simulated by PREST179 element for the convenience for applying loads and displacements to the pretension area. At the same time, a beam element is simulated by beam element BEAM44. The material of the beam is isotropic and its properties are: elasticity modulus is 2.06×105Mpa, Poisson ratio is 0.3, and unit weight equals is 7.85×103kg/m3. The FE element of flange joint in undamaged state and the equivalent beam element shown in Figs. 7 and 8, respectively.

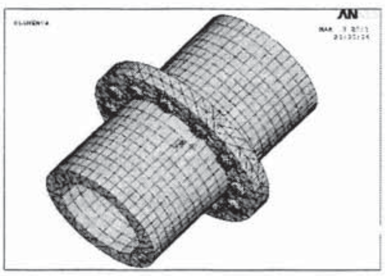

Fig.7. The FE element of flange joint in undamaged state

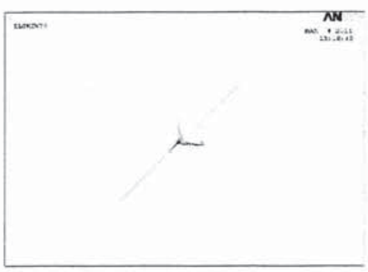

Fig.8. The equivalent beam element

According to the proposed method, the stiffness matrix of the equivalent beam element is determined when the blots in four symmetric flange joints are loosened. Hence, by assembling the stiffness matrix of the equivalent beam element of the damage flange joints with those of other members, the stiffness matrix of the finite element model of the tower is then formulated.

3.3 Simulation of wind-induced response for damaged state

In this example, an artificial simulation of the fluctuating wind is used as the load excitation. In the simulation, Davenport spectrum is used for the fluctuating wind speed, the terrain roughness coefficient $\alpha = 0.16$ is assumed, the time step of the fluctuating wind speed equals 0.02s is adopted, and the simulation time is taken as 250s in order to obtain the stable mean deviation of the strain responses. Fluctuating winds are simulated by a harmonic superposition method under the mean wind pressure of 0.3KN/m2 and 0.6KN/m2 at standard height of 10 meters. The strain responses of all flange joints are obtained by external excitations of the fluctuating wind loads with the mean wind pressure of 0.3KN/m2. The wind-induced responses of the tower in the undamaged state are simulated by using the wind load with the mean wind pressure of 0.6KN/m2. The longitudinal strain response curves of the 19th flange joint in both cases are shown in Figs. 9 and 10.

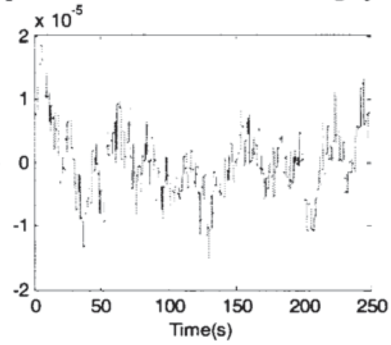

Fig. 9. Strain responses at the19th flange joint in the undamaged state.

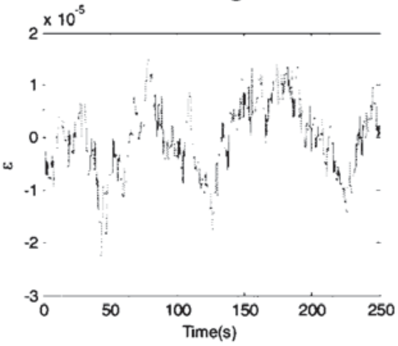

Fig. 10. Strain responses at the19th flange joint in the damaged state.

3.4 Damage index

Because the wind loads are different, the damage locations of bolt looseness cannot be found directly from Figs 9 and 10. The standardized damage index of each flange joint can be calculated and then be used to form a damage index vector. The results for the damage index are shown in Fig. 11.

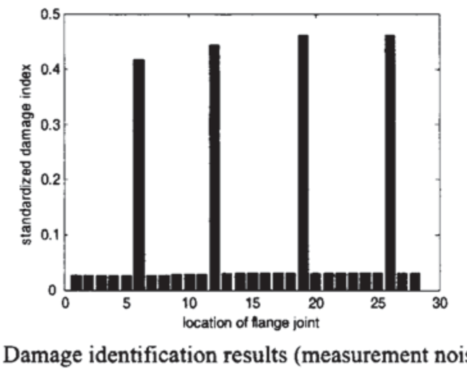

Fig. 11. Damage identification results (measurement noises 0%).

It can be seen from Fig. 11 that at the simulated damage locations (6, 12, 19, and 26) the standardized damage index has a substantial change and the standardized damage index at the other locations is almost equal to 0. This indicates that the abrupt change of damage index can be used to identify the locations of the bolt looseness accurately and effectively.

4 Conclusions

This paper developed a method for detecting the damage locations of bolt looseness at the flange joints of the tower leg members in high-rising steel tubular towers. It can be concluded from the study that:

(1) The standardized damage index, which was proposed in this paper for identification of the damage locations of the bolt looseness at flange joints in high-rise steel tubular tower, is sensitive to the damage locations but is independent of the wind load.

(2) When the bolts of the flange joints are loosened, the damage index vector proposed in this paper can be used to detect the locations of loosening effectively and accurately.

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