Research Article

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Load identification and fatigue evaluation via wind-induced attitude decoupling of railway catenary

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Abstract: In strong wind area, wind vibration on key railway catenary components may lead to safety hidden danger like fatigue failures. In this work, a load identification approach was proposed by decoupling the wind-induced suspension attitude to acquire the hard-to-get environmental wind load and evaluate the catenary fatigue damage on railway catenary. In theoretical modeling, mechanical relation between wind load and registration displacement is formulated in pure lateral and vertical loading by finite element analysis. Wind load is identified via suspension attitude decoupling into displacement under individual load. Nodal forces, as the external load acting on catenary connections between supporting beams, are further correlated with the identified wind load to calculate the structural stress of catenary components. In experiment, visual detection is used to measure the wind-induced attitude of catenary suspension in wind area, where maximum wind speed climbs up to 41 m/s. Experimental results are transferred into wind loads and nodal forces using the proposed model. Stress spectra and fatigue damage evaluation of connection components are carried out adopting the rain-flow counting method and damage accumulation rule.

Research outcome certifies that the proposed methodology provides an effective means to evaluate the fatigue behavior of railway catenary in wind area.

Keywords: load identification, stress calculation, railway catenary, attitude decoupling, fatigue damage evaluation

1 Introduction

Wind safety remains a top concern when the railway catenary system is subjected to strong alternating wind vibrations [1], especially for railway lines in wind areas like Xinjiang Uighur Autonomous Region of China, where its historical maximum wind speed can reach 64 m/s. Unlike railway catenary in non-wind area, there is a higher possibility of mechanical failures and malfunctions at key catenary components in wind area [2]. Figure 1 shows some typical wind-induced failures like abrasion, fracture, and breakdown on critical connections and suspension wires from field investigation which occurred along Lanzhou-Xinjiang railway line in the 100 km wind area. All those wind-induced malfunctions, if not found and removed timely, may give rise to accidents like pantograph-catenary damage because of severe impacts and malposition, short circuiting arc, and voltage disengagement because of pantograph-catenary disconnection. During wind seasons, railway department makes efforts to deal with these frequent emergent events exhaustedly. However, those sudden and random maintenances affect unfavorably to the busy railway transportation.

For electrified railways in wind area, wind-induced mechanical failures [3,4] at key catenary components, if not found and treated timely, may give rise to hidden danger to railway operation safety. In response to this problem, China Railway Corporation (CRC) has arranged 10 special wind tests on train operation safety in Lanzhou-Xinjiang Passenger Railway line [5–9]. The main concern of those tests is to optimize the transition between

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Figure 1: Wind-induced failures of railway catenary components from field investigation. (a) Abrasion of ball-head hanging ring; (b) wire clamp breakdown; (c) electric link fracture; (d) binaural link plate detachment; (e) dropper nylon sleeve detachment; (f) suspension pulley clamping stagnation.

different windbreak facilities, including heightening the windbreak walls [10]. Adopted measures, to a certain extent, can protect the train from strong wind-induced vibrations, but worsen the flow at catenary suspension. Wind safety on railway catenary becomes more prominent [11].

Related research on railway catenary safety was performed in terms of aerodynamic behavior of catenary wire, wind-induced movement of catenary suspension, and fatigue evaluation [12] by pantograph-catenary dynamics and stochastic wind filed simulation. In windless area, the work load on railway catenary mainly comes from pantograph-catenary interaction forces. The transient response of catenary suspension in a single span is calculated by the dynamic contact force between pantograph and catenary when the train passes through the span with different speeds [13]. The fatigue load spectra on messenger wire, droppers, contact wire [14], registration point, cantilever beams [15], and anchor ear [16] are then obtained by stress wave propagation [17], dynamics analysis [18], stress–strength interference [19], etc. The load spectra are used to evaluate the service reliability at the most unfavorable location of catenary structure [20]. In wind area, stochastic wind field simulation is a popular method when studying the fatigue performance of catenary structure [21,22]. Simulations involve Monte Carlo method [23], Harmony Superposition method [24], Linear Filtering method [25], Wavelet Filtering method [26], Stochastic Fourier method [27], Autoregressive model [28], etc. Time-history of lateral and vertical wind is acquired by Davenport and Panosfsky power spectra, respectively [29]. Structural stress is obtained by

numerical simulation in wind loading and transferred into stress load spectra using the simulated wind time-history and rain-flow counting method. The wind attack angle [30] and probability distribution of average wind speed [31] are taken into account in evaluation. Catenary fatigue research based on stochastic wind simulation considers the probability distribution of historical wind speed in local area, but fails to represent the real wind-induced loads on catenary suspension. There is a limit in fatigue evaluation by pure stochastic wind simulation.

In aerodynamic research of catenary wire, numerical simulation is adopted considering the original section [32], wearing section [33–35], and icing section [36,37] to analyze the galloping oscillation and aerodynamic coefficient of catenary wire under different wind speed and attack angle. In addition, scaled wind tunnel test is performed to measure the resistance along wind direction, the lift force in lateral direction, and the torsion in vertical direction [38,39] to find the influence from wind attack angle on aerodynamic parameters of catenary wire model [40]. Research outcomes can offer evidence for calculating the wind loads in different wind speed and wind attack angle.

The conceptual idea of this work is to identify the real wind load on railway catenary by observing the wind-induced suspension attitude. In catenary attitude detection, the machine vision method is commonly adopted for its environmental adaptability. Methods include the vehicle-mounted detection [41,42] and ground detection [43]. The vehicle-mounted system detects geometric parameters including the height and stagger of catenary

wire. The ground detection system measures the wind vibration of catenary suspension using a special reflective target installed at key locations [44]. The method requires additional installation of target plates, which brings risks in train operation safety in case of connection failures. Therefore, it is necessary to propose catenary movement detection technology, considering the feasibility of observing targets, anti-interference of identification algorithm, and stabilization of camera vibration.

In this work, a novel wind load identification model was proposed by decoupling the wind-induced catenary suspension attitude, and the identified wind loads were further used in catenary finite element analysis (FEA) model to get the structural stress at key catenary components, as an aid to develop the stress load spectra from detected wind-induced suspension vibration. The developed load spectra was then implemented into fatigue damage spectra to calculate the overall damage, as an evidence for estimating the left service life of catenary components, as well as structural optimization and catenary maintenance cycle recommendation. In the following sections, model description in Section 2.1, load identification in Section 2.2 and stress calculation in Section 2.3 were all presented in Section 2. Experiment analysis of wind-induced attitude recognition model and visual inspection of suspension vibration were introduced in Section 3, which gives experiment data including suspension motion and environmental wind speed. At last, fatigue evaluation of load spectra development, fatigue damage calculation, and fatigue evaluation were shown in Section 4. Technical route of the proposed work is shown in Figure 2.

2 Theoretical formulation

Railway catenary is a system of overhead wires used to supply electrical power to a locomotive, or an EMU motor car equipped with a pantograph. Catenary system consists of catenary suspension, locator, support pole, and cantilever, as shown in Figure 3. Messenger wire, as an important carrying component of catenary suspension, is hung at a specific designed tension between line structures. The contact wire is held in tension by messenger wire, attached to which at frequent intervals by clamps and droppers. To make it best for current collection, the contact wires are straight and parallel to the rail track with the aid of messenger wire and droppers. On straight railway line, the contact wires are zigzagged to the left and right of the center from each support to the next, so that the pantograph slide wears evenly.

Regularly, railway catenary works under the pure impacts from pantograph-catenary interaction when the train passes through, if there is no environmental wind. The impact gives rise to frequent malfunction at registration components. However, when the catenary system is subjected to strong wind, the induced vibration will result in severe wear on most of the connections. To find the wind characteristic on railway lines in Xinjiang, on-site experiment of the wind speed and direction was performed at different height and location beside the railway catenary suspension in 2017, as shown in Figure 4. By statistically counting the occurrence of wind angles, the prevailing wind angle is the cross wind vertical to the railway catenary suspension. During the test, the maximum wind speed is

Figure 2: Technical route of the proposed method.

Figure 3: Railway catenary system and its components.

25 m/s, whereas the wind data are typical along all other areas in Xinjiang railway. Therefore, in the following theoretical modeling, wind load on the catenary suspension is divided only in two directions, lateral and vertical directions in the plane perpendicular to the railway line. The wind along railway line is not concerned because it does not contribute to the wind-induced suspension vibration, and it is much smaller than the prevailing cross wind.

In FE model of the catenary, suspension wires and support structures that include the locator, cantilever, insulator, and support pole are all modeled in simplified beam elements with the same section, material property of the real components. The contact and messenger wires

are meshed in designed pretension. The nodes between different structural beams describe the component connections, the nodal forces of which are read in simulation before precise FEA on the connection components. Stress calculation is then performed with given nodal forces. Therefore, the following sections, respectively, present the FE model description, wind load identification, and structural stress calculation.

2.1 FE model description

In FEA with ABAQUS/CAE commercial software, a local coordinate system is created at the registration point, where the x -axis is along the lateral direction, y -axis is along the vertical direction, and z -axis is along the railway line. Only half of the suspension span (20 m) is modeled centering about the catenary support pole because of its geometric and loading symmetry. Symmetric constraint is applied at the two ends of catenary suspension, in which the displacement along z -axis and rotation about x -axis and y -axis are set to zero. To make a general solution between the environmental wind load, nodal displacement, and nodal force, all catenary components are modeled with BEAM elements. Mechanical parameters of catenary components are listed in Table 1.

Before FE modeling of the overall railway catenary system, the initial shape of the suspension is the first step

Figure 4: Wind measurement on railway line in Xinjiang.

Table 1: Mechanical parameters of catenary components

Component	Material	Elastic modulus E (GPa)	Poisson's ratio ν	Density ρ (g/cm ³)
Contact wire	CuMg ₁₂₀	124	0.3	8.94
Messenger wire	CuMg ₁₂₀	124	0.3	8.94
Dropper	06Cr ₁₉ Ni ₁₀	206	0.3	7.85
Cantilever	Q345	206	0.3	7.85
Locator	Q345	206	0.3	7.85
Support pole	Q345	206	0.3	7.85
Rod insulator	SiC	55	0.25	3.10

to ascertain. The catenary system tested on-site has no hanging invasions because of the high bridge, and no ice coating because of the dry climate. The dead weight of suspension is only considered to determine its initial shape. In railway catenary suspension, the pre-sag of contact wire is compensated by the lift forces from the messenger wire aided with droppers. In FEA, the initial configuration of catenary suspension greatly affects the accuracy of its numerical model. The solution for catenary equilibrium state is to find the initial suspension shape according to the specific design parameter [45]. The separation method is proposed here by decomposing the catenary suspension into the messenger wire and dropper system, as well as the contact wire and dropper system, to determine the pre-sag of the messenger wire and the dropper lengths, as shown in Figure 5.

In mechanical equilibrium of catenary suspension, the catenary wire is segmented by droppers. Each segment is supported by the locator or a dropper, which can be regarded as a small segment of free suspended cable, as the dashed hanging line in Figure 5. The support forces on locators and dragging forces on droppers can therefore be calculated by adding the 50% supported weight of each suspension segment at both sides, when all connections between droppers and catenary wire are in level position. Therefore, dragging forces from droppers in

catenary wire-dropper system are calculated in equation (1) as follows:

$$T_S = (L_S + L_M) \cdot g_c / 2, \quad T_M = L_M \cdot g_c, \quad (1)$$

where T_S is the dragging force from the first and last dropper at two ends, T_M is the dragging force from droppers in the middle, L_S is the distance between locator and its adjacent dropper ($L_S = 5,000$ mm), L_M is the distance between droppers at middle ($L_M = 6,000$ mm), and g_c is the weight of catenary wire per unit length ($g_c = 13.271$ N/m). Accordingly, the dragging forces from all droppers are $T_S = 73.0$ N, $T_M = 79.6$ N.

In messenger wire-dropper system, the shape of single messenger wire is numerically simulated with the gravity force acting evenly along the whole span, and the concentrating dragging forces from all droppers at connection locations underneath. In FEA, the pretension force of catenary wire and messenger wire are denoted by T_{CW} (25 kN) and T_{MW} (25 kN), respectively. The weight of messenger wire per unit length is denoted by g_m (13.145 N/m). The messenger wire is meshed into 400 BEAM elements, pre-stress of which is defined as 166.7 MPa to represent the 25 kN-pretension in wire section area both of 120 mm². After simulation, nodal displacement along the whole span in 40 m is depicted in Figure 6.

Figure 5: Equilibrium state calculation by separate model method.

Figure 6: Nodal displacement of messenger wire after shape finding.

The FE model of messenger wire is defined by creating nodes with same coordinates as its simulated configuration in shape finding. Catenary wire is modeled with meshed nodes in level. Beam elements are modeled between nodes in pretension stress of 166.7 MPa for both messenger wire and catenary wire. Droppers are created as connection between catenary wire and messenger wire. After shape finding, gravity no longer acts on both wires to maintain the suspension equilibrium state as in shape finding.

Apart from catenary suspension, support structures including the locator, cantilever beam, insulator, and support pole are modeled with simplified beam elements in half span (20 m) at two sides considering its geometrical symmetry, as shown in Figure 7. The nodes at the span ends are set in symmetric constraint on the translation freedom along z -axis, the rotation freedom about x -axis and y -axis. The spring element is modeled between the positioning tube and cantilever beam in stiffness of 7.67 N/mm, which is calibrated in experiment.

2.2 Wind load identification

Cross wind is the prevailing wind along railway line in Xinjiang, according to the on-site wind test results at different heights and locations. The wind load F_W is considered as acting in a 2D plane which is perpendicular to the direction along railway line. In this plane, the wind load can be decomposed into lateral and vertical forces (respectively denoted as F_{WL} and F_{WV}), acting on suspension wires, cantilever beams, and support structures. For each wind load, there is a 2D displacement at registration point because of structural deformation under environmental wind load and the load transmitted from catenary suspension. Therefore, the practical registration displacement under coupled wind load can be decoupled into 2D displacements under individual wind loading, as shown in Figure 8. Theoretical formulation between suspension attitude and wind load follows this decoupling rule as stated.

Figure 7: Catenary components and positioning spring modeling.

Figure 8: Wind loading decoupling rule on suspension attitude.

In lateral wind loading, the wind-induced displacement at registration point is denoted as X_{WL} in lateral direction and Y_{WL} in vertical direction, respectively. Mechanical relation between lateral wind load and 2D displacement is described in equation (2) as follows:

$$\begin{aligned} X_{WL} &= f_{WL}(\mathbf{F}_{WL}) \\ Y_{WL} &= g_{WL}(\mathbf{F}_{WL}), \end{aligned} \quad (2)$$

where $f_{WL}()$ and $g_{WL}()$ are the mathematical function that relates lateral force with lateral and vertical registration displacement, respectively, which are acquired by data fitting from FEA simulations in pure lateral wind loading.

In vertical wind loading, resulting displacement at registration point is denoted by X_{WV} in lateral direction and Y_{WV} in vertical direction, respectively. Mechanical relation between vertical load and 2D displacement is described in equation (3) as follows:

$$\begin{aligned} X_{WV} &= f_{WV}(\mathbf{F}_{WV}) \\ Y_{WV} &= g_{WV}(\mathbf{F}_{WV}), \end{aligned} \quad (3)$$

where $f_{WV}()$ and $g_{WV}()$ are the mechanical function that respectively relates vertical force with lateral and vertical registration displacement, acquired by data fitting from FEA simulations in pure vertical wind loading.

In coupled loading, the environmental wind load is decomposed into two perpendicular wind loads. Accordingly, the resulting registration displacement can be calculated as the blend of displacement induced by lateral and vertical loading, respectively. Therefore, the registration displacement under environmental wind load F_W is given in equation (4) as follows:

$$\begin{aligned} X_W &= X_{WL} + X_{WV} = f_{WL}(\mathbf{F}_{WL}) + f_{WV}(\mathbf{F}_{WV}) \\ Y_W &= Y_{WL} + Y_{WV} = g_{WL}(\mathbf{F}_{WL}) + g_{WV}(\mathbf{F}_{WV}), \end{aligned} \quad (4)$$

where X_W and Y_W are the resulting lateral and vertical displacement at registration point under coupled wind loading, respectively.

Load identification is the solution of lateral wind load $\mathbf{F}_{WL}$ and vertical wind load $\mathbf{F}_{WV}$ from the system of two element equation as (4). In FEA simulation, environmental wind load is defined with 12 load cases in the range of the historical maximum wind speed, 64 m/s, to obtain adequate fitting data from both directions. As the wind load magnitude differs from catenary components because of their different windage area, predefined wind load is described in the wind pressure other than the wind force, so that the load unit is unified on all catenary components. In calculation, wind pressure and wind force are given in equations (5) and (6), respectively, as follows:

$$Q_W = 0.5 \cdot \rho \cdot v_W^2, \quad (5)$$

$$F_W = C_W \cdot A_W \cdot Q_W, \quad (6)$$

where Q_W is the wind pressure, ρ is the air density (1.2 kg/m³ in normal temperature and pressure), and v_W is the wind speed in equation (5). C_W is the aerodynamic shape factor of catenary components (1.1 for suspension wires, 0.9 for tubular support structure [46]), and A_W is the projected area of the component in equation (6).

In different load cases, calculation results of nodal displacement at registration point are listed with wind pressure, wind load, and wind speed in Table 2.

Mathematical function is formulated by fitting the registration displacement and wind pressure in two directions as shown in Figure 9 and equation (7). The correlations between lateral pressure and 2D registration displacement, vertical pressure and vertical registration displacement follow a linear relationship. while there is a second-order polynomial relation between vertical pressure and lateral registration offset.

Table 2: Simulation results in lateral and vertical wind loading

Load case		Wind pressure (Pa)	Wind speed (m/s)	Wind force (N)			Displacement (mm)	
				Catenary suspension	Support pole	Cantilever beam	Lateral	Vertical
1#	Lateral	2,500	63.3	2558.4	7087.5	341.64	31.53	3.42
	Vertical	2,500	63.3	2,400	0	5371.65	-1.65	174.91
2#	Lateral	2,000	56.6	2046.72	5,670	273.312	25.23	2.73
	Vertical	2,000	56.6	1,920	0	4297.32	0.75	139.93
3#	Lateral	1,500	49.0	1535.04	4252.5	204.984	18.92	2.05
	Vertical	1,500	49.0	1,440	0	3222.99	2.12	104.95
4#	Lateral	1,000	40.0	1023.36	2,835	136.656	12.61	1.37
	Vertical	1,000	40.0	960	0	2148.66	2.45	69.96
5#	Lateral	500	28.3	511.68	1,417.5	68.328	6.31	0.68
	Vertical	500	28.3	480	0	1074.33	1.74	34.98
6#	Lateral	-500	-28.3	-511.68	-1417.5	-68.328	6.31	0.68
	Vertical	-500	-28.3	-480	0	-1074.33	-2.78	-34.98
7#	Lateral	-1,000	-40.0	-1023.36	-2,835	-136.656	12.61	1.37
	Vertical	-1,000	-40.0	-960	0	-2148.66	-6.60	-69.96
8#	Lateral	-1,500	-49.0	-1535.04	-4252.5	-204.984	18.92	2.05
	Vertical	-1,500	-49.0	-1,440	0	-3222.99	-11.46	-104.95
9#	Lateral	-2,000	-56.6	-2046.72	-5,670	-273.312	25.23	2.73
	Vertical	-2,000	-56.6	-1,920	0	-4297.32	-17.36	-139.93
10#	Lateral	-2,500	-63.3	-2558.4	-7087.5	-341.64	31.53	3.42
	Vertical	-2,500	-63.3	-2,400	0	-5371.65	-24.29	-174.91

Figure 9: Fitting curve between 2D nodal displacement and wind pressure..

$$\begin{aligned}
 X_{WL} &= f_{WL}(\mathbf{F}_{WL}) = C_{XWL} \cdot \mathbf{F}_{WL} \\
 X_{WV} &= f_{WV}(\mathbf{F}_{WV}) = C_{XWV1} \cdot \mathbf{F}_{WV}^2 + C_{XWV2} \cdot \mathbf{F}_{WV} \\
 Y_{WL} &= g_{WL}(\mathbf{F}_{WL}) = C_{YWL} \cdot \mathbf{F}_{WL} \\
 Y_{WV} &= g_{WV}(\mathbf{F}_{WV}) = C_{YWV} \cdot \mathbf{F}_{WV},
 \end{aligned} \quad (7)$$

where C_{XWL} is the fitting coefficient between lateral offset and lateral wind pressure ($C_{XWL} = 1.2613 \times 10^{-2} \text{ mm/Pa}$), C_{XWV1} and C_{XWV2} are the coefficients between lateral offset and vertical wind pressure ($C_{XWV1} = -2.0755 \times 10^{-6} \text{ mm/Pa}^2$, $C_{XWV2} = 4.5273 \times 10^{-3} \text{ mm/Pa}$), C_{YWL} is the

Figure 10: Mechanical diagram of the locator.

coefficient between vertical offset and lateral wind pressure ($C_{YWL} = 1.3669 \times 10^{-3} \text{ mm/Pa}$), and C_{YWV} is the coefficient between vertical offset and vertical wind pressure ($C_{YWV} = 6.9964 \times 10^{-2} \text{ mm/Pa}$).

To explain, the mechanical model of the locator can be simplified as a beam model with one hinged end O, one free end with vertical wind load F_{WV} , and the spring attached point where a resistance force F_{SPR} works in balance, as shown in Figure 10. When the locator rotates under vertical loading, the circle trajectory of the registration point gives an inflection which is defined as “Extreme” and the reference location to describe the lateral offset, when $dX_{WV}/dF_{WV} = 0$, that is $F_{WV} = -C_{XWV2}/(2C_{XWV1}) = 1090.65 \text{ Pa}$. If the vertical load is smaller or greater than that critical value, the lateral offset will not surpass the “Extreme” regardless of the elastic deformation of the locator, such as locations 【1】 and 【2】 depicted both in Figures 9 and 10.

Therefore, the movement at registration point is composed of displacements induced by lateral and vertical wind load, which are given as:

$$\begin{aligned} X_W &= X_{WL} + X_{WV} = C_{XWL} \cdot F_{WL} + C_{XWV1} \cdot F_{WV}^2 \\ &\quad + C_{XWV2} \cdot F_{WV} \\ Y_W &= Y_{WL} + Y_{WV} = C_{YWL} \cdot F_{WL} + C_{YWV} \cdot F_{WV}, \end{aligned} \quad (8)$$

where X_W and Y_W are the lateral and vertical resultant registration displacement, respectively.

The two groups of wind load solution can be analyzed through a parabolic equation acquired from equation (8) in equation (9) as below.

$$y = A \cdot F_{WV}^2 + B \cdot F_{WV} + C, \quad (9)$$

where the constant $A = C_{XWV1} \cdot C_{YWL}$, $B = C_{XWV2} \cdot C_{YWL} - C_{XWL} \cdot C_{YWV}$, and $C = C_{XWL} \cdot Y_W - C_{YWL} \cdot X_W$.

As the lateral and vertical wind load varies within $\pm 2.5 \text{ kPa}$ in scattering interval of 100 Pa , in a same description of the wind speed ranging within 63.3 m/s , the resultant registration offset X_W in lateral and Y_W in vertical are calculated after equation (8) and plotted in Figure 11(a) and (b). The maximum and minimum offset at registration point are, respectively, 55.82 and -34.00 mm in lateral direction and 178.33 mm and -178.33 mm in vertical

Figure 11: 3D plot under wind loading limits. (a) Plot of lateral offset X_W ; (b) plot of vertical offset Y_W ; (c) plot of equation component C .

Figure 12: Root selection of vertical wind load identification.

direction. The components A and B in equation (9) remain constant, while component C changes with different resultant registration offset X_W and Y_W . Figure 11(c) gives the 3D plot of component C in a range from -2.208 to 2.173 mm²/Pa, which is only related to vertical wind load F_{WV} .

In the range of variable equation component C and constant component A , B as in equation (9), the parabolic curve is shown in Figure 12, where the intersections between the curve and the axis $y = 0$ indicate the double roots. Apparently, the root on the left side varies in a reasonable range of ± 2.5 kPa, while the rightward root reveals an impossible solution as identified load.

Accordingly, the wind load identification can be reformulated in equation (10) by abandoning the impossible root at the right side.

$$F_{WV} = (-B - \sqrt{B^2 - 4A \cdot C}) / (2A)$$

$$F_{WL} = (2A \cdot Y_W + C_{YWV} \cdot B + C_{YWL} \cdot \sqrt{B^2 - 4A \cdot C}) / (2A \cdot C_{YWL}). \quad (10)$$

Validation undergoes in numerical simulation. To cover possible loading scenarios, 10 load cases of coupled wind loading are randomly generated in the range of practical scenarios. The lateral and vertical wind loads vary from $-2,500$ Pa to $2,500$ Pa. Validation load cases are illustrated in Table 3.

In each case, lateral and vertical displacements at registration point are read and substituted into the load identification model. The identified wind loads (denoted as “ID”) are compared with the given loads (denoted as “GV”). Relative deviation is calculated by $|“ID” - “GV”| / “GV” \times 100\%$ and listed in Table 4.

Comparison reveals that the deviation (“ID” – “GV”) between identified and given loads varies within -3 to

4 Pa. The relative deviation is within 0.59 and 3.39% for vertical and lateral wind load, respectively. Comparison suggests good agreement between the proposed method and numerical simulation.

2.3 Structural stress calculation

On the beam-modeled catenary support structure, the nodal forces at connections are defined in two directions in the local coordinate system other than the global system. In the local system, if the nodal force is perpendicular to the beam which is embraced by the connection component, it is defined as the axial nodal force. If along the beam, the nodal force is described as the shear force.

Table 3: Load cases in simulation validation by random method (Unit: Pa)

Parameter/ function	F_{WV} (–2,500 to 2,500 Pa) 5,000 [0.5 – rand()]	F_{WL} (–2,500 to 2,500 Pa) 5,000 [0.5 – rand()]
Load case 1#	–2,076	–797
Load case 2#	–309	–1,276
Load case 3#	296	–1,546
Load case 4#	1,085	–2,334
Load case 5#	2,011	–921
Load case 6#	–1,140	–124
Load case 7#	–526	1,834
Load case 8#	1,578	2,024
Load case 9#	1,294	853
Load case 10#	1,052	–849

NOTE: “rand()” is the random function that varies in the range of 0.0–1.0.

Table 4: Comparison between identified and given results in validation simulation

Load case	Displacement (mm)		F_{WV} (Pa)			F_{WL} (Pa)		
	Lateral X_W	Vertical Y_W	ID	GV	DEV (%)	ID	GV	DEV (%)
Load case 1#	-28.3	-146.1	-2,073	-2,076	0.16	-789	-797	0.42
Load case 2#	-17.6	-23.5	-311	-309	0.50	-1,268	-1,276	0.24
Load case 3#	-18.3	18.5	295	296	0.59	-1,541	-1,546	0.01
Load case 4#	-26.9	72.7	1,084	1,085	0.08	-2,326	-2,334	0.12
Load case 5#	-10.8	139.4	2,011	2,011	0.03	-914	-921	0.17
Load case 6#	-9.4	-79.8	-1,138	-1,140	0.18	-125	-124	3.39
Load case 7#	20.2	-34.1	-523	-526	0.64	1,837	1,834	0.12
Load case 8#	27.5	113.0	1,576	1,578	0.16	2,025	2,024	0.18
Load case 9#	13.2	91.5	1,291	1,294	0.25	859	853	0.08
Load case 10#	-8.2	72.4	1,052	1,052	0.02	-848	-849	0.46

NOTE: "ID" represents "Identified," "GV" represents "Given," and "DEV" represents "relative deviation."

From the previous section, the wind loads in the global coordinate system are identified by the registration displacement which can be measured via visual detection. The nodal forces at each connection can thereby be given in relation with wind loads as below.

$$\begin{aligned}
 R_S^{(i)} &= R_{S\_WL}^{(i)} + R_{S\_WV}^{(i)} = H_{WL}^{(i)} (F_{WL}) \\
 &\quad + H_{WV}^{(i)} (F_{WV}) \\
 R_A^{(i)} &= R_{A\_WL}^{(i)} + R_{A\_WV}^{(i)} = J_{WL}^{(i)} (F_{WL}) \\
 &\quad + J_{WV}^{(i)} (F_{WV}),
 \end{aligned} \quad (11)$$

where $R_S^{(i)}$ and $R_A^{(i)}$ are the shear and axial reaction force at component connection $i\#$ ($i = 1-9$), the numbering and name of which are shown in Figure 13. H_{WL} and H_{WV} are the functions between nodal shear force and lateral wind load, vertical wind load, respectively. J_{WL} and J_{WV} are the

functions between nodal axial force and lateral wind load, vertical wind load, respectively. Above functions suggest a linear relationship between wind loads and nodal forces.

Therefore, nodal axial and shear force calculation can be reformulated in equation (12) as below in terms of coefficient matrix.

$$\begin{Bmatrix} R_S^{(i)} \\ R_A^{(i)} \end{Bmatrix} = \begin{bmatrix} C_{S\_WL}^{(i)} & C_{S\_WV}^{(i)} \\ C_{A\_WL}^{(i)} & C_{A\_WV}^{(i)} \end{bmatrix} \cdot \begin{Bmatrix} F_{WL} \\ F_{WV} \end{Bmatrix}, \quad (12)$$

where $C_{S\_WL}^{(i)}$ and $C_{S\_WV}^{(i)}$ are the transfer coefficient from lateral wind pressure, vertical wind pressure to nodal shear force for component $i\#$, respectively. $C_{A\_WL}^{(i)}$ and $C_{A\_WV}^{(i)}$ are the transfer coefficient from lateral wind pressure and vertical wind pressure to nodal axial force for component $i\#$, respectively.

Figure 13: Connection components numbering and precise FE modeling.

Table 5: Correlation between nodal force and wind pressure (Unit: N/Pa)

Component ID	Nodal shear force $R_S^{(i)}$		Nodal axial force $R_A^{(i)}$	
	Lateral wind load C_{S_WL}	Vertical wind load C_{S_WV}	Lateral wind load C_{A_WL}	Vertical wind load C_{A_WV}
①	0.1324	0.4636	0.4942	-0.1242
②	0.0000	0.4849	0.5117	0.0000
③	0.0852	1.3123	0.2783	2.6196
④	-0.0852	0.1764	0.7451	-2.7321
⑤	0.1865	-0.1465	0.1639	-0.0735
⑥	0.1865	-0.1465	0.1639	-0.0735
⑦	-0.0988	-0.5500	0.4856	-0.8638
⑧	0.0261	0.8638	-0.0988	-1.0300
⑨	0.0179	-0.4797	-0.5114	-0.0168

Reading nodal forces at the nine connection nodes in the same load cases as set in wind load identification, the mechanical relation between nodal forces and global wind pressure can be acquired in Table 5, where the four coefficients are accordingly listed as four columns. Connection components' numbering and detailed FE model are shown in Figure 13.

For each connection component, the structural stress is computed in individual model with precise mesh. Intentions include the strength check and fatigue damage assessment of the initial component structure, as well as the component after structural optimization under the same given nodal forces. Therefore, further calculation from nodal forces at connections to the structural stress of the full-size component can be given in equation (13) as below.

$$\begin{Bmatrix} \sigma_x^{(i)} \\ \sigma_y^{(i)} \\ \sigma_z^{(i)} \\ \tau_{xy}^{(i)} \\ \tau_{yz}^{(i)} \\ \tau_{xz}^{(i)} \end{Bmatrix} = \begin{bmatrix} C_{xx\_S}^{(i)} & C_{xx\_A}^{(i)} \\ C_{yy\_S}^{(i)} & C_{yy\_A}^{(i)} \\ C_{zz\_S}^{(i)} & C_{zz\_A}^{(i)} \\ C_{xy\_S}^{(i)} & C_{xy\_A}^{(i)} \\ C_{yz\_S}^{(i)} & C_{yz\_A}^{(i)} \\ C_{xz\_S}^{(i)} & C_{xz\_A}^{(i)} \end{bmatrix} \cdot \begin{Bmatrix} R_S^{(i)} \\ R_A^{(i)} \end{Bmatrix}$$

$$= \begin{bmatrix} C_{xx\_S}^{(i)} \cdot C_{S\_WL}^{(i)} + C_{xx\_A}^{(i)} \cdot C_{A\_WL}^{(i)} & C_{xx\_S}^{(i)} \cdot C_{S\_WV}^{(i)} + C_{xx\_A}^{(i)} \cdot C_{A\_WV}^{(i)} \\ C_{yy\_S}^{(i)} \cdot C_{S\_WL}^{(i)} + C_{yy\_A}^{(i)} \cdot C_{A\_WL}^{(i)} & C_{yy\_S}^{(i)} \cdot C_{S\_WV}^{(i)} + C_{yy\_A}^{(i)} \cdot C_{A\_WV}^{(i)} \\ C_{zz\_S}^{(i)} \cdot C_{S\_WL}^{(i)} + C_{zz\_A}^{(i)} \cdot C_{A\_WL}^{(i)} & C_{zz\_S}^{(i)} \cdot C_{S\_WV}^{(i)} + C_{zz\_A}^{(i)} \cdot C_{A\_WV}^{(i)} \\ C_{xy\_S}^{(i)} \cdot C_{S\_WL}^{(i)} + C_{xy\_A}^{(i)} \cdot C_{A\_WL}^{(i)} & C_{xy\_S}^{(i)} \cdot C_{S\_WV}^{(i)} + C_{xy\_A}^{(i)} \cdot C_{A\_WV}^{(i)} \\ C_{yz\_S}^{(i)} \cdot C_{S\_WL}^{(i)} + C_{yz\_A}^{(i)} \cdot C_{A\_WL}^{(i)} & C_{yz\_S}^{(i)} \cdot C_{S\_WV}^{(i)} + C_{yz\_A}^{(i)} \cdot C_{A\_WV}^{(i)} \\ C_{xz\_S}^{(i)} \cdot C_{S\_WL}^{(i)} + C_{xz\_A}^{(i)} \cdot C_{A\_WL}^{(i)} & C_{xz\_S}^{(i)} \cdot C_{S\_WV}^{(i)} + C_{xz\_A}^{(i)} \cdot C_{A\_WV}^{(i)} \end{bmatrix} \cdot \begin{Bmatrix} F_{WL} \\ F_{WV} \end{Bmatrix}, \quad (13)$$

where $C_{xx\_S}^{(i)}$, $C_{yy\_S}^{(i)}$, $C_{zz\_S}^{(i)}$, $C_{xy\_S}^{(i)}$, $C_{yz\_S}^{(i)}$, and $C_{xz\_S}^{(i)}$ are the transfer coefficient from nodal shear force to the 6-component stress. $C_{xx\_A}^{(i)}$, $C_{yy\_A}^{(i)}$, $C_{zz\_A}^{(i)}$, $C_{xy\_A}^{(i)}$, $C_{yz\_A}^{(i)}$, and $C_{xz\_A}^{(i)}$ are the transfer coefficient from nodal axial force to the 6-component stress. The structural stress is only the nodal force-induced stress and excludes the structural pre-stress because of bolt pre-tightening.

The FE modeling of connection components can be categorized into four kinds, the contact clamp (component ①), messenger clamp (component ②), support base (components ③ and ④), and bushing ears (components ⑤–⑨). The meshed FE models, their boundary conditions, and loading locations are illustrated in Figure 14.

In the mesh model, linear hexahedral and quadratic tetrahedral elements are adopted to fit the complex components configuration. The mesh size is set to 2 mm to enhance simulation accuracy. Material properties of the connection components are as follows: elastic modulus $E = 206$ GPa, Poisson's ratio $\nu = 0.3$, density $\rho = 7.85$ g/cm³. For each connection component, the mesh properties, boundary constraint, and loading areas are defined as follows:

- (1) Contact clamp: FE model consists of 225,360 elements and 252,763 nodes. The hollow cylinder at the top is connected with the locator, the inner surface is therefore set in radial constraint and the bottom is vertically constrained. Axial and shear loading are both applied on the clamp area at bottom. The pretension is set to 12.5 kN on the two bolts to simulate pre-tightening as shown in Figure 14(a).
- (2) Messenger clamp: The model has 822,306 elements and 306,486 nodes. The bottom clamp links the top cantilever beam through two bolts, the inner face and bolt holes are set in radial constraint. Nodal axial and shear

Figure 14: Detailed FE model of connection components. (a) Contact clamp; (b) messenger clamp; (c) support base; (d) bushing ears.

forces are applied on the inner face of top clamps which embraces the messenger wire. The four tightening bolts are in 18.3 kN-pretension as shown in Figure 14(b).

- (3) Support base: The mesh is comprised of 580,891 elements and 443,666 nodes. The left hoop embraces the support pole through double long bolts in pretension of 18.3 kN. The inner face of the hoop is set in radial constraint and vertical translation restriction. The nodal axial force is applied on the connecting bolt, which is in pretension of 18.3 kN as well. Nodal shear force is applied on its neighboring level planes as shown in Figure 14(c).
- (4) Bushing ears: There are 257,210 elements and 373,719 nodes in FE model. The hinged hoop attaches the cantilever beam through two bolts in pretension of 12.5 kN. The inner hoop face is set in radial constraint and the translation restriction along the embraced beam. Nodal axial and shear force are applied on the bolt connecting to the other beam. The pretension of the bolt is set in 18.3 kN as shown in Figure 14(d).

To cover all possible nodal forces under the lateral and vertical wind load range in ± 2.5 kPa, wind load scattering is generated in an interval of 100 Pa to combine 2D wind loads, and nodal axial and shear forces are calculated according to equation (12) on those scattering wind

loads. After that, the nodal force range for each connection component is confirmed based on the minimum and maximum value on above scatterings, as listed in Table 6. However in stress calculation, the acting nodal forces on connection components are not the exact calculated nodal force range. All nodal force calculations are rounded up to the closest outer bound in unit of 50 N, as the nodal force input in stress calculation simulation, which is denoted as “FE range” in Table 6. For each kind of component, the nodal force range in FE simulation starts from the minimum and ends at the maximum extreme, because what the structural stress correlates with the nodal axial and shear force for each component kind is the same even at different connections.

For each component type, nodal force range in FE simulation is segmented into seven uniformly spaced scatters. In pure axial loading and shear loading, six-component stress of parent metal and bolts at stress concentration locations are read and fitted with nodal forces in distinct magnitude. A linear relationship is observed between stress and nodal forces, and the transfer coefficients are listed in Table 7 for nodal axial force and shear force, respectively. For connection components, parent metal and bolts are individually analyzed because of their different material properties. The initial stress of connection components is also given in Table 7 because of bolts

Table 6: Nodal force range and FE load magnitude definition (Unit: N)

Component type	Component ID	Nodal shear force $R_S^{(i)}$		Nodal axial force $R_A^{(i)}$	
		Calculation range	FE range	Calculation range	FE range
Contact clamp	①	±1490.0	±1,500	±1546.0	±1,550
Messenger clamp	②	±609.7	±610	±817.4	±850
Support base	③	±1569.4	±1,600	±3051.7	±3,100
	④	±324.0		±1343.3	
Bushing ears	⑤	±454.1	±1,100	±340.2	±1,700
	⑥	±454.1		±340.2	
	⑦	±625.7		±1696.3	
	⑧	±1061.5		±1205.0	
	⑨	±620.2		±799.0	

pre-tightening. The contour plot of von Mises stress of four component categories is illustrated in Figure 15.

As revealed above, stress concentrating region mainly occurs around the bolts and installing hole, no matter whether it is of axial or shear loading. This is, on one hand, because of the bolt pre-tightening and, on the other hand, the axial and shear forces transmission via bolt connections. Taking account into the higher stress and weaker material properties of the parent metal on components, bolts are no longer considered in the following analysis.

In fatigue stress calculation, the standard von Mises stress is calculated as equation (14).

$$\sigma_{vm}^{(i)} = \sqrt{\frac{1}{2}[(\sigma_x^{(i)} - \sigma_y^{(i)})^2 + (\sigma_y^{(i)} - \sigma_z^{(i)})^2 + (\sigma_x^{(i)} - \sigma_z^{(i)})^2] + 6(\tau_{xy}^{(i)2} + \tau_{yz}^{(i)2} + \tau_{xz}^{(i)2})} \quad (14)$$

The standard calculation is generally a poor choice for fatigue evaluation. The range acquired from the strictly positive history of the von Mises stress does not include any potentially negative part of the stress cycle. The signed von Mises stress (SVM), which can take the negative values, is thus given by equation (15) as the stress calculation rule.

$$\sigma_{svm}^{(i)} = \text{sign}(I_1^{(i)}) \cdot \sigma_{vm}^{(i)}, \quad (15)$$

where $I_1^{(i)}$ is the first stress invariant, $I_1^{(i)} = \sigma_x^{(i)} + \sigma_y^{(i)} + \sigma_z^{(i)}$.

Table 7: Transfer coefficient from nodal force to the six-component stress and initial stress

	Connection components	Contact clamp	Messenger clamp	Support base	Bushing ears
Axial force factor (MPa/kN)	$C_{xx\_A}^{(i)}$	42.32	34.07	20.24	6.47
	$C_{yy\_A}^{(i)}$	113.14	-60.56	3.91	2.02
	$C_{zz\_A}^{(i)}$	-25.42	127.02	7.24	-5.19
	$C_{xy\_A}^{(i)}$	8.61	-14.66	4.95	0.98
	$C_{yz\_A}^{(i)}$	-2.62	12.37	-5.73	-61.83
Shear force factor (MPa/kN)	$C_{xz\_A}^{(i)}$	94.84	-14.13	1.45	15.09
	$C_{xx\_S}^{(i)}$	0.23	2.05	60.22	77.63
	$C_{yy\_S}^{(i)}$	0.71	-10.54	23.39	27.46
	$C_{zz\_S}^{(i)}$	0.12	2.28	25.12	29.64
	$C_{xy\_S}^{(i)}$	-0.54	-0.54	-1.09	-27.63
Pre-stress (MPa)	$C_{yz\_S}^{(i)}$	0.24	10.57	-21.49	15.38
	$C_{xz\_S}^{(i)}$	108.35	-11.71	5.44	-6.99
	$S_{xx0}^{(i)}$	-49.99	-46.57	42.73	175.30
	$S_{yy0}^{(i)}$	-178.52	-11.83	14.36	43.18
	$S_{zz0}^{(i)}$	-4.53	-172.64	17.16	63.10
	$S_{xy0}^{(i)}$	3.70	7.65	2.25	-42.47
	$S_{yz0}^{(i)}$	0.27	-7.15	-77.02	-2.59
	$S_{xz0}^{(i)}$	15.84	-35.79	19.49	-1.16

3 Field experiment

In this section, a visual detect approach of catenary suspension attitude is proposed [47]. The registration point, acting as the moving target, is coated with reflectorized paint for better recognizability in observation. Object in background is observed as the static target to compensate detecting errors induced by supporting vibrations. Template matching method for moving and static target is developed to fit in complicated imaging conditions assisted with the environment-adaptive template refreshing principle. On-site wind test is then conducted using the proposed detecting method. The lateral and vertical attitude of catenary registration point is acquired and analyzed.

Figure 15: Stress concentration contour plot of the four connection components. (a) Bushing ears under axial force; (b) bushing ears under shear force; (c) support base under axial force; (d) support base under shear force; (e) messenger clamp under axial force; (f) messenger clamp under shear force; (g) contact clamp under axial force; (h) contact clamp under shear force.

3.1 Visual detection model

Wind test of catenary suspension was carried out at one end of Sangequan Grand Bridge in Nanjiang railway line, where frequent pantograph operation faults were reported because of vertical wind-induced uplift to catenary wire.

To get the best viewpoint and illumination conditions, area-array CCD cameras were installed between cantilever mounting bases on catenary support pole. The camera is DS-2CD5A24FWD-IZH, manufactured by HIKVISION. Image sampling rate is set to 24 image frames per second, which surely covers low frequency characteristic requirement of wind-induced vibration of catenary suspension (mostly 1.2–1.8 Hz) [47]. Infrared light source was set along with the camera during nighttime to avoid the risk of mistaking visible lighting source as the train operation signal light. At the registration point, reflective coating is used to enhance the visibility of dynamic detecting target, the motion of which is observed by the

camera in terms of image pixel offset. The mileage plate serves as the static target to represent the wind-induced camera vibration. On one hand, image of the plate demonstrates a signboard with numbers on it at daytime, and a white light-reflecting plate at nighttime. On the other hand, the plate is regarded as a static point even in the strongest wind because of large rigidity of the steel portal structure, as shown in Figure 16.

The imaging model between actual and image pixel offset of observing target is given as equation (16).

$$\begin{Bmatrix} \Delta X \\ \Delta Y \end{Bmatrix} = \begin{bmatrix} \frac{L_R}{L_P} & 0 \\ 0 & \frac{L_R}{L_P} \end{bmatrix} \cdot \begin{Bmatrix} \Delta x \\ \Delta y \end{Bmatrix} = \begin{bmatrix} K_C & 0 \\ 0 & K_C \end{bmatrix} \cdot \begin{Bmatrix} \Delta x \\ \Delta y \end{Bmatrix}, \quad (16)$$

where $\{\Delta X, \Delta Y\}$ and $\{\Delta x, \Delta y\}$ denote the 2D actual and pixel offset of the target, respectively. L_R and L_P denote the actual and pixel size of the target, respectively. K_C represents the self-calibration coefficient, which values 2.7 mm/pixel at the registration point.

Figure 16: Wind-induced attitude recognition scheme.

To enhance detection efficiency, image processing is performed in a subregion where the registration point movement does not exceed the transverse and vertical boundary even under the strongest wind. A rectangle target template is predefined to compare with the matching area transversely and vertically by pixels, as shown in Figure 17. The matching difference between target template and matching area is formulated as equation (17).

$$D(k, l) = \sqrt{\frac{\sum_{i=1}^{y_{LIM}} \sum_{j=1}^{x_{LIM}} [G_{OBJ}(i, j) - G_{IMG}(i, j)]^2}{x_{LIM} \cdot y_{LIM}}}, \quad (17)$$

where $G_{OBJ}(i, j)$ and $G_{IMG}(i, j)$ denote the gray-scale value of pixel point at coordinate (i, j) in target template and image matching area, respectively. x_{LIM} and y_{LIM} denote the pixel length and width of the target template. X_{LIM} and Y_{LIM} denote the pixel length and width of image processing sub-region. Parameters k and l represent the

Figure 17: Target template matching and 3D contour plot of matching difference [47].

pixel coordinate of the present matching area in vertical and transverse direction, which are calculated as in equation (18).

$$\begin{aligned} k &= 1 \sim Y_{\text{LIM}} - Y_{\text{LIM}} + 1 \\ l &= 1 \sim X_{\text{LIM}} - X_{\text{LIM}} + 1, \end{aligned} \quad (18)$$

By calculating the matching difference between matching area and target template of registration point, the 3D contour map is illustrated in Figure 17. The matching difference peak reaches the minimum when the target template coincides with the matching area, which indicates the pixel location of identified registration point target.

Pixel coordinates of the identified target are denoted as (k_0, l_0) . The modified target pixel coordinates are then corrected with target template size considered, as in equation (19).

$$\begin{aligned} k_{\text{OBJ}} &= k_0 + \frac{Y_{\text{LIM}}}{2} \\ l_{\text{OBJ}} &= l_0 + \frac{X_{\text{LIM}}}{2}. \end{aligned} \quad (19)$$

In detection, the gray feature of pixels in target area varies because of illumination changes from day to night. Therefore, if the target template remains constant as the initial template, it will fail to match the actual target in the present image. To better fit in complex illumination, the target template is updated by the recognized target at each processing image frame.

In addition, a threshold for matching difference to tell whether the matching area is the target is defined as T . The threshold T is determined by the maximum of all minimum matching differences after processing all image frames over 24-h period. The optimal threshold T , which values 5.0, is substituted into all image frames to recognize the target and calculate the deviation between recognized target location and actual position. Calculation indicates that the maximum deviation is within only 2.7 mm in engineering dimension, which proves that the optimal threshold contributes to the best recognition results both in accuracy and efficiency.

Strong wind gives rise to camera vibration on the support pole and brings about the false displacement of dynamic target detected in the camera. To eliminate the detection error, a static target is set via the mileage plate on the steel portal structure in the background. The mileage plate remains stationary in the most unfavorable wind environment because of the large rigidity of steel portal structure. Moreover, imaging of the plate presents a numbered signboard during daytime and a white rectangle plate during nighttime, which can be easily

captured by the camera. Through detection, the transverse and vertical false displacements of static target are denoted by Δx_{STA_i} and Δy_{STA_i} , respectively. The transverse and vertical displacements of dynamic target, the registration point, are denoted by Δx_{DYN_i} and Δy_{DYN_i} , respectively. Accordingly, the absolute displacements of dynamic target referred to the background are given in equation (20).

$$\begin{aligned} \Delta X_{\text{MOV}_i} &= K_C \cdot (\Delta x_{\text{MOV}_i} - \Delta x_{\text{STA}_i}) \\ \Delta Y_{\text{MOV}_i} &= K_C \cdot (\Delta y_{\text{MOV}_i} - \Delta y_{\text{STA}_i}), \end{aligned} \quad (20)$$

where ΔX_{MOV_i} and ΔY_{MOV_i} indicate the absolute transverse and vertical displacement of registration point in image $i\#$ (unit in mm), respectively.

The detection precision of presented method depends on the pixel size and resolution of the camera. In this work, the resolution of the detecting camera is $1,920 \times 1,080$, the target area of registration point is 53×31 pixels, describing the real size of $50 \text{ mm} \times 29 \text{ mm}$. Therefore, the minimum motion that can be detected by the visual detection system is $50 \text{ mm}/53 \text{ pixels} = 0.94 \text{ mm}$ for each pixel. Considering the relative deviation 1.8% of the visual detection stated in ref. [47], the recognition capacity and deviation determines the minimum motion, that is, $0.94 \text{ mm} \times (1 + 1.8\%) = 1.02 \text{ mm}$.

3.2 Results and discussion

In wind test of one catenary span at Sangequan Grand Bridge in Nanjiang railway line, the environmental wind speed was tested by anemometer, which was set 50 m away from the railway bridge perpendicularly.

To get a more clear view of the wind changes, the environmental wind speed data were averaged per 10 min. The experimental data, which includes the wind speed and 2D suspension displacement, are selected lasting 24 h from 5:00 on September 24, 2017. The time-history curve of the transverse and vertical displacement to the 10-min mean wind speed is shown in Figure 18.

From the experiment, it is observed that the wind speed climbs up to 41 m/s from 16 m/s, and then drops to 14 m/s. The magnitude of wind-induced attitude of registration point shows a similar trend to that in wind speed. The maximum vertical target displacement reaches 86.7 mm and -21.3 mm , which is 6.7 times greater than that transversely (12.9 and -17.7 mm). It is explained that the vertical target movement is affected by the vertical spring at the registration root, while the transverse

Figure 18: Transverse and vertical absolute displacement to wind speed curve.

target movement is mainly determined by the rigidity and elasticity of the registration tube.

4 Fatigue evaluation

In this section, the wind-induced attitude at catenary registration point, which is detected on site in wind area, is transferred into 2D wind load at catenary suspension, nodal forces at connection nodes and ultimate structural stress on individual components. The resulting stress time-history is developed into load spectra in different grades. Fatigue damage is accordingly analyzed with spectra grades for convergence to give the recommended spectra grade for catenary fatigue evaluation. Under the suggested spectra grade, fatigue damage of the four connection components, which undergo the more severe structural stresses, is assessed and extended to the designed life based on the statistical data of wind speed measurement along railway line.

The S–N curve is derived by its mean fatigue life and the standard deviation of $\log N$. The mean S–N curve shows that 50% or 99.9% of the specimens will fail. The basic design S–N curve is given as

$$\log N = \log C - m \cdot \log S, \quad (21)$$

where S is the stress amplitude (MPa), N is the number of cycles to failure, and m and C are S–N coefficients related to material properties, specimen form, stress ratio, and loading modes.

The Goodman line is used to estimate the numerical relationship between stress amplitude S_a and element mean stress S_m . Symmetrical cyclic stress for equivalent life transition is given as shown in equation (22).

$$S_{cyc} = \frac{S_{ys}}{S_{ys} - S_m} \cdot S_a, \quad (22)$$

where S_{cyc} , S_a , S_m , and S_{ys} denote the symmetrical cyclic stress, the amplitude stress, the mean stress, and the yield strength of connection components, respectively. The transferred cyclic stress is updated in 2D load spectra to calculate fatigue damage in cooperation with number of load cycles, which are acquired from rain-flow counting.

In fatigue damage accumulation rule, there is a given fatigue strength on the basis of the loading path and stress magnitude for any material. The fatigue strength is reduced in a certain amount of each loading cycle. When the accumulated damage in this cycle approaches the material fatigue strength, failure comes in higher possibility. To relate the loading cycles and fatigue strength, Miner's damage accumulation rule is hereby adopted. The total fatigue damage of 2D load spectra is calculated in equation (23).

$$D = \sum_{i=1}^n \sum_{j=1}^n \frac{N_{ij} \cdot S_{cyc\_ij}^m}{C}, \quad (23)$$

where N_{ij} and S_{cyc_ij} are the load cycle counts and transferred symmetrical cyclic load at amplitude load of grade i and mean load of grade j , m and C are the constants of S–N curve, and n is the load spectra grade number.

The material of connection components is Q345C for parent metal. Table 8 gives the material properties under the survival rate (SR) of 50 and 99.9%, respectively.

4.1 Load spectra development

The load spectra used in catenary design for service life and damage tolerance assessment are based on a

Table 8: Material properties of connection components [48]

Material property	Parent metal	
Survival rate (SR)	50%	99.9%
S–N coefficient m	7.8050	5.5716
S–N coefficient C	1.14×10^{24}	2.76×10^{18}
Fatigue limit S_{LIM} /MPa	153	113
Yield strength S_{YS} /MPa	327	284
Elastic modulus E /GPa	206	206
Poisson's ratio ν	0.3	0.3

predicted average usage. It is important for catenary safety and maintenance planning reasons to acquire the real load spectra because the inspection intervals are based on the predicted spectra. In this work, the procedure in use to handle the tracking of real service loads is making use of the recorded wind-induced registration attitudes and the theoretical model to identify the loads indirectly. Peak values of the nodal forces and SVM stress at 9 connection components are listed in Table 9. Time-history of the greatest in each component type is given according to the recorded displacement of catenary registration point in Figure 19.

To calculate the total fatigue damage, time domain-based methods are often used by applying deterministic methods, such as the rain-flow counting algorithm. Rain-flow counting is easier to use but requires higher computational or experimental effort, and the approach that is most widely used in different fields and standard codes, as well as part of the framework of classic fatigue theory. Its outstanding feature is that a series of closed stress-strain hysteresis loops are determined according to the nonlinear relationship between the measured material stress and strain. The actual measured load history is simplified into several load cycles, and the stress load

spectra are compiled for the subsequent estimation of fatigue life.

In rain-flow counting, the load cycles counted from the recorded real service load data are grouped according to the limit of mean and amplitude of each load cycle when 2D load spectra are concerned. If all load cycles are grouped into n grades, the interval between adjacent grades is calculated as equation (24):

$$\begin{aligned} G_M &= (S_{M\_MAX} - S_{M\_MIN})/n \\ G_A &= (S_{A\_MAX} - S_{A\_MIN})/n, \end{aligned} \quad (24)$$

where G_M and G_A are the interval between adjacent grade of mean and amplitude load cycles, respectively. S_{M_MAX} and S_{M_MIN} are the maximum and minimum of mean load among all load cycles, respectively. S_{A_MAX} and S_{A_MIN} are the maximum and minimum of amplitude load among all load cycles, respectively.

Thus, the boundaries for the i th grade load spectra are calculated in equation (25) as follows:

$$\begin{aligned} S_{M(i)LOW} &= S_{M\_MIN} + (i - 1) \cdot G_M, \\ S_{M(i)UP} &= S_{M\_MIN} + i \cdot G_M \\ S_{A(i)LOW} &= S_{A\_MIN} + (i - 1) \cdot G_A, \\ S_{A(i)UP} &= S_{A\_MIN} + i \cdot G_A, \end{aligned} \quad (25)$$

where $S_{M(i)LOW}$ and $S_{M(i)UP}$ are the lower and upper limits of the i th grade load spectra for mean load cycles, respectively. $S_{A(i)LOW}$ and $S_{A(i)UP}$ are the lower and upper limits of the i th grade load spectra for amplitude load cycles, respectively.

The rain-flow counting will statistically count the load cycles depending on which grade of the load spectra they belong to, both in mean and amplitude load cycles. To find the best group number in balance with calculation efficiency and precision, 2D fatigue damage which

Table 9: Peak values of nodal forces and structural stress at connection components

Component type	Component ID	Nodal shear force (N)		Nodal axial force (N)		SVM stress (MPa)	
		Max	Min	Max	Min	Max	Min
Contact clamp	①	452.57	−1028.11	1843.80	−973.82	281.88	29.68
Messenger clamp	②	511.46	−817.373	609.68	−150.85	278.45	104.49
Support base	③	1569.41	−384.15	3051.70	−862.67	263.93	114.05
	④	324.00	−118.81	1343.28	−4264.80	153.73	114.23
Bushing ears	⑤	200.92	−454.07	166.34	−340.15	158.76	113.79
	⑥	200.92	−454.07	166.34	−340.15	158.76	113.79
	⑦	216.88	−625.74	642.10	−1696.26	201.71	116.26
	⑧	1061.46	−260.21	329.83	−1205.01	262.99	134.64
	⑨	155.10	−620.16	799.03	−511.99	161.77	110.84

Note: “SVM” is short for “Signed Von Mises.”

Figure 19: Time-history of nodal forces and SVM stress of connection components. (a) Nodal forces at contact clamp; (b) SVM at contact clamp; (c) nodal forces at messenger clamp; (d) SVM at messenger clamp; (e) nodal forces at support base (bottom); (f) SVM at support base (bottom); (g) nodal forces at bushing ears (top frame anchor); (h) SVM at bushing ears (top frame anchor).

considers both mean and amplitude stress is computed in distinct groups from 2, 4, 8, 16, 32, 64, 128, 256, to 512 grades. Taking into account the most unfavorable circumstance, 1D load spectra are not involved because the mean stress remains positive for all components and therefore contributes to the equivalent cyclic amplitude stress and fatigue damage. Resulting damage of the

experimental test is transformed into base-10 logarithm to fit the plot range in challenge of damage differences, respectively, for each component kind with maximum stress at selected locations, as seen in Figure 20.

Results reveal that from 32 or more groups, fatigue damage remains unchanged for contact clamp, messenger clamp, and bushing ears. However for support

Figure 20: Fatigue damage convergence with load spectra group number.

base, the convergence starts from the 64 groups. It is recommended that 64-grade load spectra are adopted in wind-induced fatigue assessment for railway catenary system. In the following sections, all evaluations go in 64-grade to meet calculation precision and efficiency.

After stress transformation and spectra developing, 2D SVM stress spectra are plotted in 64 grades respectively for

contact clamp, messenger clamp, bushing ears, and support base, as shown in Figure 21.

Above spectra indicates that the stress amplitude climbs up to 115, 87, 75, and 64 MPa, respectively, for contact clamp, messenger clamp, support base, and bushing ears. However, load cycles concentrate in the amplitude stress range of 0–15 MPa, which accounts for 63.9% of the

Figure 21: 2D load spectra of SVM stress in 64 grades. (a) Contact clamp; (b) messenger clamp; (c) support base at bottom; (d) bushing ears at top frame anchor.

Table 10: Damage calculation in the 24-h wind test

Component	SR (%)	Fatigue damage	
		1D	2D
Contact clamp	50	8.71×10^{-8}	2.58×10^{-4}
	99.9	1.74×10^{-6}	5.69×10^{-4}
Messenger clamp	50	9.14×10^{-9}	5.84×10^{-6}
	99.9	3.89×10^{-7}	1.23×10^{-4}
Support base	50	2.73×10^{-9}	3.01×10^{-6}
	99.9	1.30×10^{-7}	9.72×10^{-5}
Bushing ears	50	1.22×10^{-9}	1.89×10^{-6}
	99.9	7.65×10^{-8}	7.39×10^{-5}

total cycle counts in mean stress range of 129–187 MPa for the contact clamp, and 71.12% of the total counts in mean stress range of 147–201 MPa for the messenger clamp. For support base and bushing ears, the spectra concentration deviates to a lower mean stress region of 122–156 MPa and 136–166 MPa, and contributes 65.8 and 78.0% of the total cycle counts in stress amplitude range of 1–10 MPa, respectively. Spectra distribution difference can be explained with the initial stress because of different pre-tightening of connecting bolts.

4.2 Fatigue damage evaluation

In calculation of fatigue damage from the 64-grade SVM stress spectra in Figure 21, the sum of damage in the 24 h wind test for four connection components is listed in Table 10. The results are given in terms of 50 and 99.9% SR, 1D and 2D load spectra.

It is seen that the contact clamp suffers the largest damage, followed by the messenger clamp, support base, and bushing ears. It is also revealed that the 2D damage is more than two times of 1D damage, because the positive mean SVM stress contributes to the amplitude of transferred cyclic stress.

According to the statistics of the fatigue damage of the four connection components, the contour map can be obtained as shown in Figure 22.

Unlike the VM stress spectra, amplitude stress from 0 to 30 MPa of the contact clamp, which accounts for 93.7% of all load cycles, contributes only 1.7% of the total fatigue damage. However, amplitude stress from 30 to 115 MPa gives 98.3% contribution of the total damage. Amplitude stress ranges of 55–87 MPa, 47–75 MPa, and 44–64 MPa account for 61, 49, and 68% of the total damage, respectively, for messenger clamp, bottom support base, and bushing ears in 99.9% SR.

To extend the fatigue damage in the test to the designed life of catenary components, meteorological data of wind days (>20.4 m/s) from 2015 to 2020 are statistically collected from wind monitoring station at Sangequan Grand Bridge, in divisions from the 8th wind grade ($v_{w8} = 19.0$ m/s) to the 17th ($v_{w14} = 43.8$ m/s). To make it equivalent in wind load magnitude, the maximum wind speed tested in field experiment is defined as $v_{wts} = 41$ m/s, statistically counted in wind monitoring station are denoted as $v_{w8} = 19.0$ m/s, $v_{w9} = 22.6$ m/s, $v_{w10} = 26.5$ m/s, $v_{w11} = 30.6$ m/s, $v_{w12} = 34.8$ m/s, $v_{w13} = 39.2$ m/s, $v_{w14} = 43.8$ m/s, $v_{w15} = 46.8$ m/s, $v_{w16} = 53.5$ m/s, $v_{w17} = 58.7$ m/s, respectively, for the 8th, 9th, to the 17th-grade wind. Wind days for each wind grade are described as $N_8, N_9, N_{10}, N_{11}, N_{12}, N_{13}, N_{15}, N_{16}$, and N_{17} . Taking the quadratic power relation between wind pressure and wind speed, the equivalent annual wind days is given in equation (26) as below.

$$N_{EQV} = \sum_{i=8}^{17} \left(\frac{v_{wi}}{v_{wts}} \right)^2 \cdot N_i. \quad (26)$$

Wind day counts categorized by the wind grade from 2015 to 2020 are given in terms of column bar plot as shown in Figure 23. Equivalent wind day calculations based on equation (26) are 178.8, 201.3, 196.2, 205.8, 175.3, and 171.7 days, respectively, from 2015 to 2020. Thus, equivalent wind days in damage extension to 1 year is the average of wind days in the concerning 6 years, which makes 188.2 days per year.

In extension of the fatigue damage from the 24 h experimental calculation to the designed life cycle, the equivalent damage of all components is computed by the multiplying of experimental damage, equivalent annual wind days, and the designed life years. Therefore, the equivalent fatigue damage and estimated life are given in Table 11 for four types of connection components under 50 and 99.9% SR, 1D and 2D stress spectra evaluation.

The rating list of equivalent fatigue damage in descending sequence is the contact clamp (1.07), bottom support base (0.458), bushing ears (0.348), and messenger clamp (0.231) in 99.9% SR. Among them, life estimation of the contact clamp is 9.3 years, which is smaller than the designed life cycle. The estimated life of other components can meet the requirement of their design, but the fatigue evaluation is performed in pure wind vibration. It is thus recommended that the maintenance period of connection components be shortened according to the fatigue behavior because of both pantograph-catenary impacts and wind-induced vibration.

Figure 22: 64-grade fatigue damage spectra of connection components. (a) Contact clamp in 50% SR; (b) contact clamp in 99.99% SR; (c) messenger clamp in 50% SR; (d) messenger clamp in 99.99% SR; (e) support base in 50% SR; (f) support base in 99.99% SR; (g) bushing ears in 50% SR; (h) bushing ears in 99.99% SR.

Figure 23: Statistical data of wind days (>20.4 m/s) in the past 6 years (“G” – is short for Grade).

5 Conclusion and prospects

In this work, an approach of wind load identification and fatigue evaluation was proposed from the overall catenary system to local connection components. The approach was validated in random loading simulation and applied in field experiment of wind-induced suspension attitude. Fatigue damage and life were estimated on key components according to the meteorological data of wind days on-site. Several conclusions are drawn as follows:

- (1) Wind load identification is presented by simulating the mechanical relation between wind pressure and 2D displacement at registration point. The formulation is validated in random load cases by FE simulation, where the maximum deviation is no greater than 8 Pa, and the relative deviation is within 3.4%. Validation suggests good agreement between the theoretical model and numerical simulation.
- (2) In overall catenary beam-based model, the environmental wind loads and nodal forces at connections are theoretically acquired through suspension registration displacement. The nodal forces, acting as the

standard load spectra from measured suspension movement, are further analyzed to obtain the structural stress of local connection components, both in evaluating its fatigue strength and structural optimization.

- (3) Field experiment of catenary suspension movement is performed by visual detection in Xinjiang railway line. The maximum vertical and lateral offsets are 86.7 and 17.7 mm, respectively, when the 10-min mean wind speed climbs up to 41 m/s. Experimental results are transferred into wind loads and nodal forces with the proposed model. Damage evaluation of connection components reveals that the optimal load spectra grade is 64 groups. In extension from the single wind experiment to the designed life cycle, the equivalent damage is calculated based on the meteorological data of wind days on site. Results indicate that the estimated life of catenary clamp is 9.3 years, which is not able to meet its designed life of 10 years. Maintenance period of all components is recommended to be shortened considering the damage contribution from both wind-induced vibration and pantograph-catenary impacts.

Table 11: Fatigue damage and life estimation of catenary connection components

Component	SR (%)	Equivalent damage		Fatigue life/year		Service life/year [49]
		1D	2D	1D	2D	
Contact clamp	50	<0.001	0.486	>100	20.6	10
	99.9	0.003	1.070	>100	9.30	
Messenger clamp	50	<0.001	0.011	>100	>100	10
	99.9	0.001	0.231	>100	43.3	
Support base	50	<0.001	0.014	>100	>100	25
	99.9	0.001	0.458	>100	54.6	
Bushing ears	50	<0.001	0.009	>100	>100	25
	99.9	<0.001	0.348	>100	71.9	

Based on fulfilled work, several prospects are given as follows:

- (1) Besides the alternating wind load, environments such as blown sand, rainfall, and ice coating have uncertain amount of influence on components abrasion. In the future, more factors will be considered to reduce field measurement errors.
- (2) The proposed model fails to consider the longitudinal wind load on catenary suspension which apparently affects a lot to the cantilever support structure. The methodology therefore works only in wind areas where cross wind is dominant. Future work will endeavor to contain the 3D wind load identification in the model.
- (3) The proposed model is dependent on catenary geometrical and physical properties. These properties affect the load estimation in a great deal. In future application, extension of load estimation influence by the span length, pre-tension force, and material properties (such like modulus and density) will be studied when changing one of those parameters and remaining the others. Acquiring the series of all individual relationships, the load estimation can include the geometrical and physical parameters by multi-dimension fitting.
- (4) To prevent or reduce fatigue damage, two ways will be used in future work.
  - Wind load reduction by flow control. Theoretical correlation between suspension wind load and windbreak wall geometry dimension, line space, embankment parameters, and environmental wind will be studied to get the minimum suspension wind load.
  - Connection component strengthening by structural and material optimization. By inputting the nodal force spectra from existing environment and catenary distribution, fatigue damage can be re-assessed after material and topological structural optimization, which provides evidence for component selection and design of railway catenary.
- (5) In the future, more tests will be performed in different areas according to the different wind characteristics to enrich the load spectra database. The work will be a strong support for railway catenary design and application.

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