

Research Article

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Multiple load recognition and fatigue assessment on longitudinal stop of railway freight car

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Abstract: Safety evaluation of key support components remains a challenge for freight trains because of the

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difficulties in direct and precise monitoring. In this work, the longitudinal stop on well-hole freight train, which prevents the cargo from sliding in anterior-posterior direction, is investigated. Load identification approach is proposed via strain perception at multiple locations, which are selected from the optimal positions sensitive to longitudinal and lateral loading in Finite Element Analysis (FEA). Validation is performed in random loading simulations. The identified loads deviate from the random sets within 4.07%. Longitudinal and lateral forces are recognized in an attempt to calculate the signed von Mises (SVM) stress of the longitudinal stop structure for fatigue evaluation. In application, the reconstructed structural stress climbs up to 107.1 MPa for the right weld base. Employing the rain-flow counting and Miner's damage rule, the recommendation for load spectra grade in convergence is 64 groups. The equivalent fatigue damage is 0.854 and it drops to 30% in the statistical annual maximum mileage equivalency. Research outcome reveals that the proposed method enables the real-time monitoring of service loads and structural stress in railway freight transport, which provides scientific evidence for its maintenance planning and structural optimization.

Keywords: load recognition, strain measurement, fatigue assessment, well-hole freight car, longitudinal stop

1 Introduction

The transportation of oversized cargoes such as turbine parts, large boilers, or power transformers by railway has

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great reliability and cost-effectiveness [1–3]. Heavy haul trains have large axle loads, and the oversized cargoes they convey are of large freight volumes. The longitudinal stops on the freight train can prevent the cargo from sliding in the anterior-posterior direction (Figure 1). Due to the longitudinal and lateral dynamic interactions when the train is accelerating, braking, and curve negotiating, coupled with the vertical force caused by the cargo, it causes multiple collisions back and forth between the cargo and the longitudinal stop [4,5], as well as the train and the track [6–8]. Therefore, the safety of the special cargo transportation and maintenance of key structure of the train needs to be considered.

To provide durable and effective solutions to the safety problems caused by the interaction of longitudinal and lateral dynamic loads, load identification, real-time monitoring, and fatigue assessment systems are required to ensure structural stability, and prevent destructive failures during cargo transportation [9,10]. Several inverse load identification methods have been previously proposed to indirectly measure dynamic loads from the responses of optimally placed sensors on the structure. In inverse load identification, the forces on the structure are considered unknown. They are reproduced from the measured dynamic response on the structure (acceleration, vibration, strain, etc.). This is the basic principle of the structural health monitoring and damage prediction system used for the full-field structural response estimation. Deterministic, stochastic, and artificial intelligence techniques have been widely used to solve these inverse load problems.

As long as the strain behavior remains linear, the measured strains can always be used to reconstruct the unknown input forces. Wang *et al.* [11] developed a

strain-measurement methodology based on a load identification algorithm for large deflection on elastic fixed thin plate structures. In structural engineering, appropriate strain sensors are installed around cantilever beams and several approximation methods are used to obtain corresponding strain results [12–16]. The strain sensor type has been taken into consideration in load identification implementation. Hong *et al.* [17] considered that the Fiber Bragg Grating strain sensor is preferred due to its linearity and multiplexing ability that is suitable for the simply supported beam structure [18]. Also, a load identification model is proposed by Hong and his team, from measured strain responses on a simply supported beam subjected to multiple loads, and the robustness has been verified [19], the strain sensor and accelerometer data are utilized to reconstruct the impact forces on shells and plates, and to determine multiple isolated structural loads and pressures in complex structures [20,21].

Dynamic programming is also widely used for inverse structural dynamics problems [22–24]. Zhu *et al.* [24] used the Bellman's principle of objective function to improve the structural load identification. In the same vein, Artificial Neural Networks have also been applied. For instance, Hui *et al.* [25] applied BP neural network to identify moving axle loads through their dynamic strains. Moreover, Artificial Neural Network can be used to identify dynamic loads on the axle(s) of vehicle-bridge dynamic systems and its accuracy is verified by experiments [26].

In this article, a theoretical load recognition and stress calculation method is proposed for the longitudinal stop of DK₃₆-type well-hole freight car. Besides, mechanical correlation between the longitudinal loads, lateral loads, and perception strains at sensitive locations are theoretically

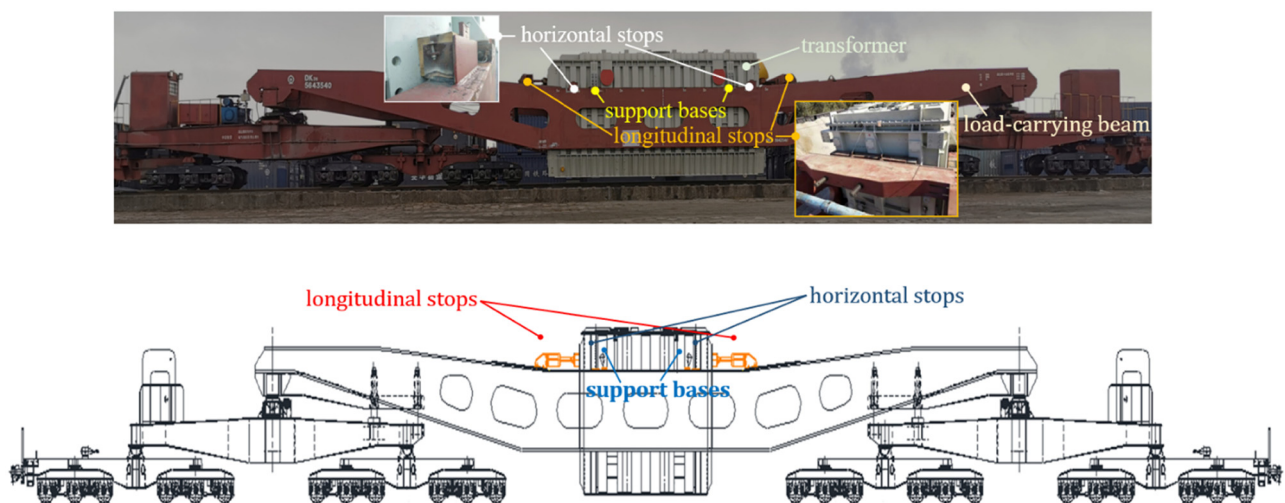


Figure 1: Schematic diagram of heavy haul freight train structure.

modeled via single loading under bending and shearing effects in Finite Element Analysis (FEA). It is validated by random coupled loading simulation, by comparison between the identified multiple loads and randomly given loads. Finally, the proposed method is applied in real-vehicle test, to determine the maximum service loads and fatigue evaluation (Figure 2).

2 Theoretical modeling

Theoretical modeling determines the load identification resultant, which includes the longitudinal and lateral forces on stop structure, based on the optimal strain perception locations in bending and shearing effects. The measured strains are decomposed into the strains induced by all service loads, giving a solution to the loads from measured strains. The structural stress, the signed von Mises (SVM) stress, is calculated from the identified loads as the fatigue evaluation spectra.

In mechanical analysis, the longitudinal stop can be regarded as a beam fixed at both ends along the cargo width, which are welded on top of two load-carrying beams. The double weld bases lay in the plane deviated to a distance

vertically from the center plane of longitudinal stop beam. The deviation brings about the bending and shearing effect, where the longitudinal and horizontal forces which are denoted as F_{L1} , F_{L2} and F_{H1} , F_{H2} , respectively, act on the jack rods. The definition of geometric dimensions of longitudinal stop beam is depicted in Figure 3 as follows.

The material of the stop beam is HG70 high-strength steel. The elastic modulus $E = 210$ GPa, the Poisson ratio $\mu = 0.3$, the density $\rho = 7,850$ kg·m⁻³, and yield stress $S_{ys} = 345$ MPa. Geometrical dimensions of the longitudinal stop beam are listed in Table 1.

2.1 Strain perception

The mechanical model of the longitudinal stop beam is a coupling of bending and shearing. For brevity in top view, the stop beam can be simplified as a simply supported beam in longitudinal loading where the concentrated forces act on the jack rods along x-axis, and the two supports stand on weld bases. Its elastic deformation along y-axis induced in bending, moves the two load-carrying beams in an allowable range of the adjustable linking bars between them, as the top-view model in Figure 4

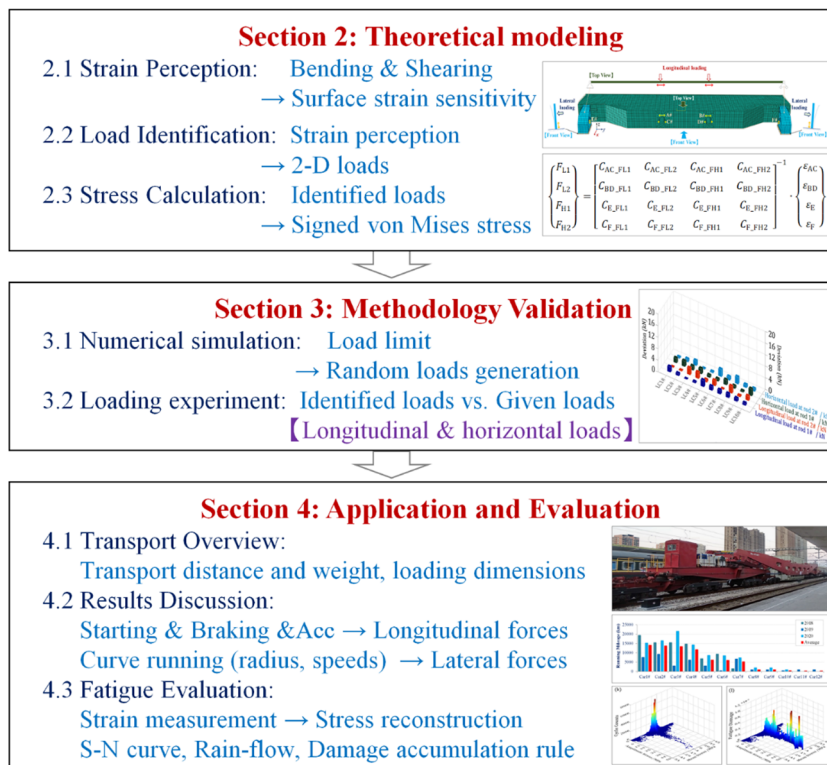


Figure 2: The framework of this article.

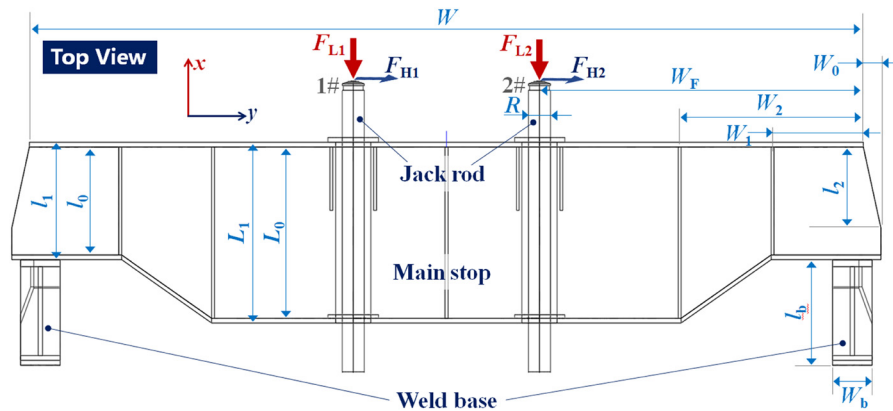


Figure 3: Geometric dimension of longitudinal stop beam.

Table 1: Geometrical dimensions (mm)

Parameter	W	W_F	W_2	W_1	W_0	R	L_1	L_0	l_1	l_0	L_2	l_b	W_b
Value	3,800	1,475	837	500	50	100	770	730	506	460	345	450	180

suggests. In horizontal loading in front view, the weld bases at two sides can be assumed as cantilever beams, the fixed end of which are welded on load-carrying beams. Horizontal forces are transmitted from jack rods to stop structure, and finally to the weld bases.

FE simulation of the longitudinal stop was performed on ABAQUS/CAE software. Full constraints were imposed on the bottom nodes at weld bases. With a mesh size of 5 mm and 8-node linear hexahedral brick element in reduced integration (C3D8R), the FE model has 9.97 thousand nodes and 8.4 thousand elements.

2.1.1 Longitudinal load-induced strain perception

In the simply supported beam model, two longitudinal forces along the jack rods deviate from the adjacent

support base by W_F , a distance between the support base and the longitudinal force on the jack rod. In the three segments divided by F_{1x} and F_{2x} , the diagram of shear force (F_S) and bending moment (M) along the beam are shown in Figure 5(b) and (c), respectively. Pure bending only occurs in the middle segment when the two longitudinal forces are the same. If the left stop force exceeds the right one, $F_{1x} > F_{2x}$, the larger reaction force R_A at base A results in greater shear force and bending moment at jack rod 1# than the other, and *vice versa*. In bending theory of simply supported beam, the bottom normal stress is in positive correlation with the bending moment as calculated in equation (1).

$$\sigma = M \cdot L_1 / (2I_z), \quad (1)$$

where I_z is the inertia moment about the neutral z -axis.

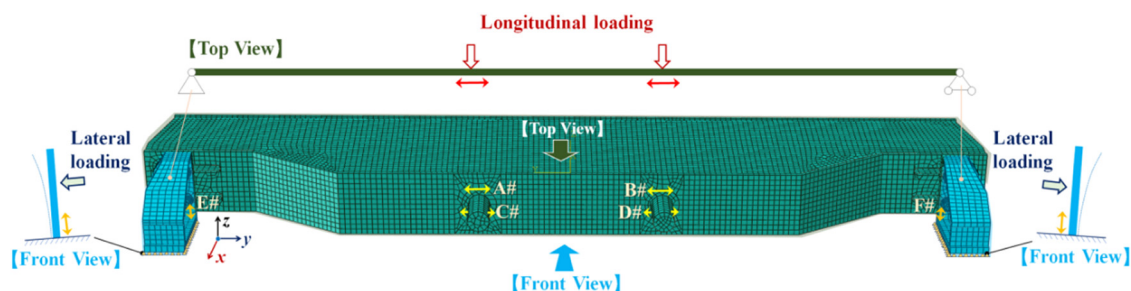


Figure 4: Mechanical model of the stop structure in longitudinal and horizontal loading.

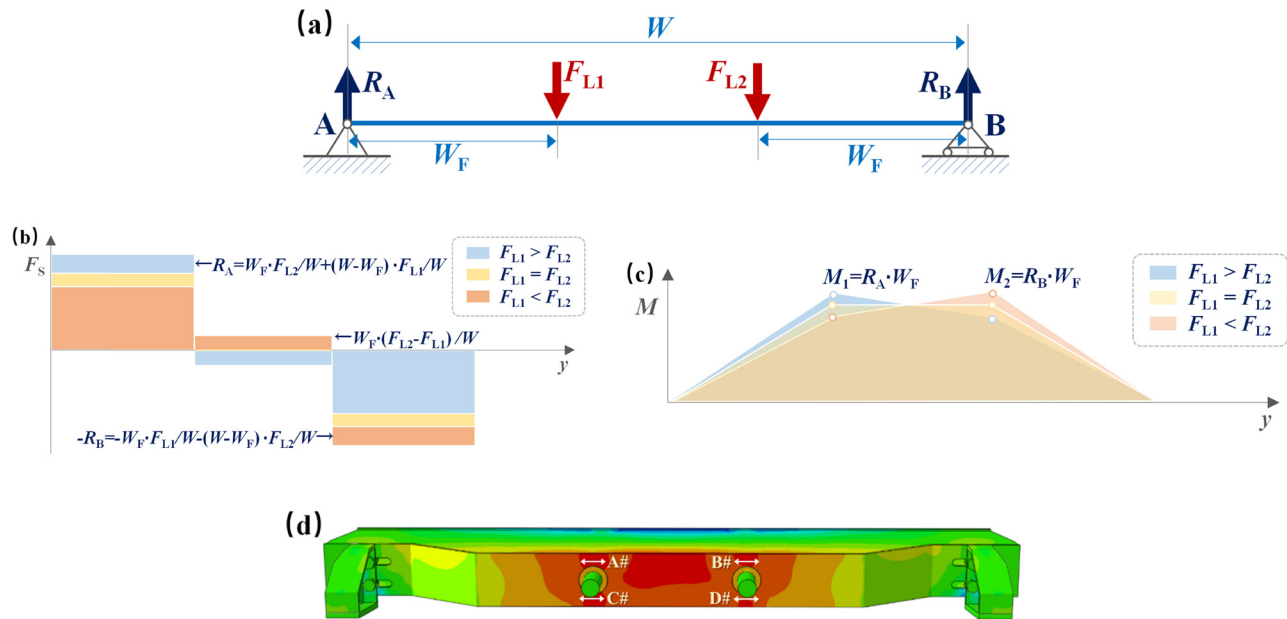


Figure 5: Simply supported beam analysis in longitudinal loading. (a) Mechanical structure; (b) shear force; (c) bending moment and (d) lateral strain.

Therefore, in longitudinal load identification, strain responses are selected at the loading locations where peak moment arises. The optimal strain measurement location is at the supported bottom side and along the length of the beam, which is proved by FE simulation in Figure 5(d). Considering the jack rods' hole at the bottom, double strain gauges are set symmetrically at two loading locations denoted by A#, B#, C# and D# as in Figure 5. The strain perception is 5 mm away from the edge of the holes.

2.1.2 Horizontal load-induced strain perception

In pure horizontal loading, the two weld bases can be regarded as a cantilever beam along z -axis, the restrained end of which is the welding base adhered to the top of the load-carrying beam. Horizontal forces originate from the friction between jack rods and stop wood, and transmit from the jack rods to the main stop and then the weld bases. The weld bases are bolted onto the main stop, horizontal loads can thus be equivalently treated as the uniform load acting on the cantilever beam, as shown in Figure 6(a).

For each weld base, it shares half of the total horizontal forces along its length in z -axis direction. The uniform load for each is described as $Q = (F_{H1} + F_{H2})/(2H)$. Hence in the bending theory of cantilever beam, the maximum shear force as well as the bending moment occurs

at the roots, where the peak shear force is $Q \cdot H$ and peak moment is $Q \cdot H^2/2$, as in Figure 6(b) and (c).

Therefore, strain perceptions in horizontal load identification are selected at the root of the weld bases. The strain measurement setup is at the bottom root of the weld bases in vertical direction, which agrees well with FE simulation in Figure 6(d). The strain perceptions are denoted as E# and F#. The strain gauges are set on the main stop which are 5 mm away from their respective bottom and weld base edges.

2.2 Load identification

2.2.1 Longitudinal loading

In single loading on the jack rods longitudinally and horizontally, four load cases are taken into account. The longitudinal force of railway cargo is determined by its inertia force in the running direction. When the cargo is in rigid reinforcement, the longitudinal inertia force per unit mass is calculated in equation (2) as below [27].

$$t_0 = \frac{\gamma}{\sqrt{m \cdot T_C + T_C^2}}, \quad (2)$$

where γ is inertia force coefficient ($\gamma = 2,160$ kN), m is the cargo mass coefficient ($m = 82$ t), and T_C is the total mass of loaded well-hole freight train. If $T_C > 200$ t, $T_C = 200$ t.

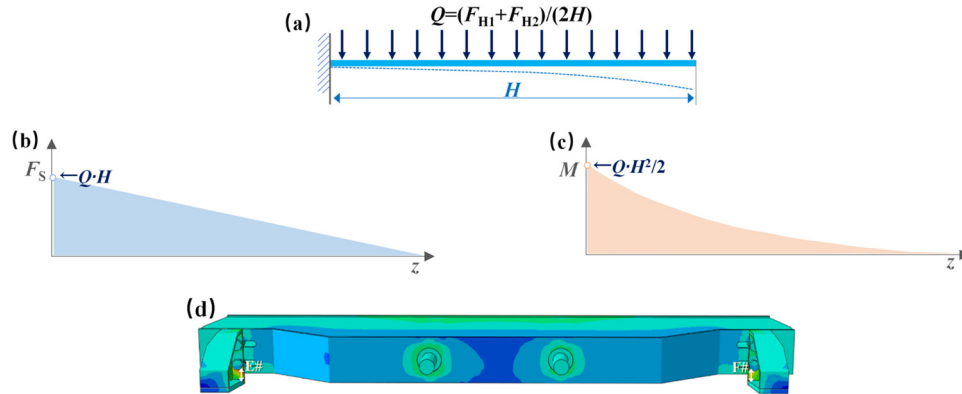


Figure 6: Cantilever beam analysis in horizontal loading: (a) mechanical structure; (b) shear force; (c) bending moment and (d) lateral strain.

For the DK₃₆-type well-hole freight train, the maximum loaded cargo is 360 t, and the empty car is 200 t. The total mass of loaded car is 560 t. The calculated longitudinal inertia force per unit mass is $t_0 = 9.095 \text{ kN} \cdot \text{t}^{-1}$. The longitudinal inertia force for 360 t cargo is 3274.3 kN. The inertia force is on one hand balanced by the frictional force between the cargo and 4 vertical support bases, which is calculated by the overall support force and the friction coefficient (here defined as 0.3). It is on the other hand balanced by the longitudinal stop forces at jack rods. From this perspective, the limit of longitudinal stop force for each jack rod is calculated in equation (3) as follows:

$$F_{L_lim} = (m_C \cdot t_0 - m_C \cdot g \cdot \mu_1) / 2, \quad (3)$$

where m_C is the maximum cargo weight, $m_C = 360,000 \text{ kg}$. g is the gravity acceleration, $g = 9.8 \text{ m} \cdot \text{s}^{-2}$. μ_1 is the friction coefficient, $\mu_1 = 0.3$ [18]. After substitution, $F_{L_lim} = 1107.94 \text{ kN}$.

Longitudinal loading at the two jack rods are set equally spaced in 4 load magnitudes from 276.99 to 1107.94 kN. Surface strain at the six perceptions are read from simulation

in Figure 7, where ε_{AC_FL1} , ε_{BD_FL1} , ε_{E_FL1} , and ε_{F_FL1} , respectively, describe the average strain at A# and C#, the average strain at B# and D#, strain at E#, and strain at F# under longitudinal loading at jack rod 1#. Strain ε_{AC_FL2} , ε_{BD_FL2} , ε_{E_FL2} , and ε_{F_FL2} , respectively, denote the above strains in longitudinal loading at jack rod 2#. Mechanical relation between resulting strains and longitudinal loading at two jack rods are given in equation (4) as below.

$$\begin{aligned} \varepsilon_{AC_FL1} &= C_{AC_FL1} \cdot F_{L1}, & \varepsilon_{AC_FL2} &= C_{AC_FL2} \cdot F_{L2}, \\ \varepsilon_{BD_FL1} &= C_{BD_FL1} \cdot F_{L1}, & \varepsilon_{BD_FL2} &= C_{BD_FL2} \cdot F_{L2}, \\ \varepsilon_{E_FL1} &= C_{E_FL1} \cdot F_{L1}, & \varepsilon_{E_FL2} &= C_{E_FL2} \cdot F_{L2}, \\ \varepsilon_{F_FL1} &= C_{F_FL1} \cdot F_{L1}, & \varepsilon_{F_FL2} &= C_{F_FL2} \cdot F_{L2}, \end{aligned} \quad (4)$$

where C_{AC_FL1} and C_{AC_FL2} denote the coefficients between the average strain of A# and C# and loading at jack rods 1# and 2#, respectively ($C_{AC_FL1} = 0.2818 \mu\text{ε} \cdot \text{kN}^{-1}$ and $C_{AC_FL2} = 0.5465 \mu\text{ε} \cdot \text{kN}^{-1}$). C_{BD_FL1} and C_{BD_FL2} denote the coefficients between the average strain of B# and D# and loading at jack rods 1# and 2#, respectively ($C_{BD_FL1} = 0.5465 \mu\text{ε} \cdot \text{kN}^{-1}$ and $C_{BD_FL2} = 0.2818 \mu\text{ε} \cdot \text{kN}^{-1}$). C_{E_FL1} and C_{E_FL2} denote the coefficients between the average strain

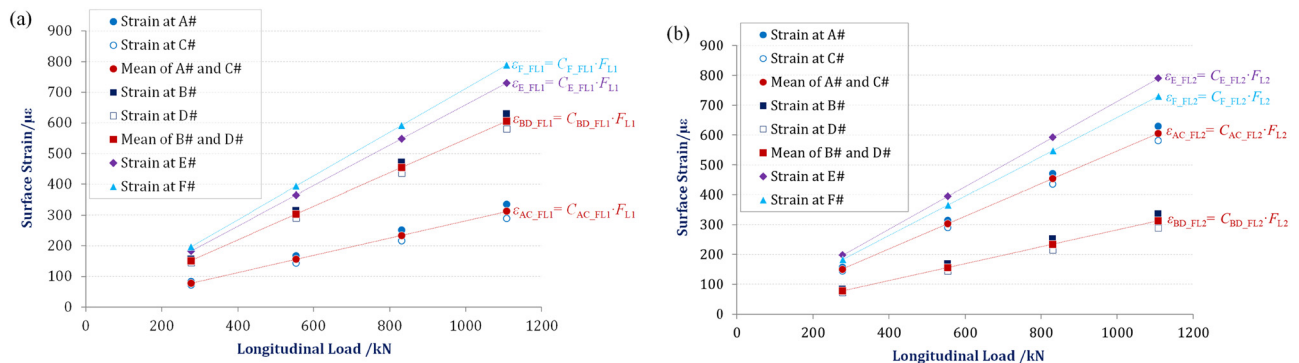


Figure 7: Surface strain response under longitudinal loading at individual jack rod: (a) load at jack rod 1# and (b) load at jack rod 2#.

at E# and loading at jack rods 1# and 2#, respectively ($C_{E_FL1} = 0.6591 \mu\epsilon \cdot kN^{-1}$ and $C_{E_FL2} = 0.7121 \mu\epsilon \cdot kN^{-1}$). C_{F_FL1} and C_{F_FL2} denote the coefficients between the average strain at F# and loading at jack rods 1# and 2#, respectively ($C_{F_FL1} = 0.7121 \mu\epsilon \cdot kN^{-1}$ and $C_{F_FL2} = 0.6591 \mu\epsilon \cdot kN^{-1}$).

Mechanical relation in Figure 7 reveals that the strains at E# and F# demonstrate a symmetric response in loading at jack rods 1# and 2# due to the geometry and loading symmetry. Same rule follows for strains at A#, C# and B#, D#. A greater response of strains is also observed at the root E# and F# than at the loading bottom A#, C#, B#, and D#. It can be explained that the bending effect at the weld bases acting as cantilever beam is more notable than the loading case as simply supported beam. However, less sensitive perceptions at A#, C#, B#, and D# are still indispensable because of the number of strain perceptions required for longitudinal and horizontal load identification at both jack rods.

2.2.2 Horizontal loading

The horizontal force arises from the friction between the jack rods and the stop wood when the train runs on line curves. The resultant longitudinal compression comprises of the dynamic load as F_{L_lim} defined in equation (3) and the pre-compression between jack rods and stop wood during loading. Hence, the limit of horizontal force for each jack rod can be calculated in equation (5) as below.

$$F_{H_lim} = (F_{L_lim} + P_{cmp}) \cdot \mu_2, \quad (5)$$

where μ_2 is the friction coefficient between the jack rods and the stop wood, $\mu_2 = 0.3$ [18]. P_{cmp} is the pre-compression between jack rods and stop wood.

The mechanical relation between the torque and the bolt preload is given by [28]:

$$P_{cmp} = \frac{1,000 M_t}{K \cdot d}, \quad (6)$$

where M_t is the tightening torque setting 2,000 N·m during on-site installation. The diameter of the jack rod is $d = 100$ mm. K is the tightening torque coefficient, which is dependent on the friction coefficient of screw thread and dimension parameter of the jack rods. Here, $K = 0.18$ in lubricant and surface zincification. Hence, the pre-compression is $P_{cmp} = 111.1$ kN. The horizontal load limit is calculated as $F_{H_lim} = 365.7$ kN.

Horizontal loading at each jack rod is set in 4 load magnitudes, -365 , -182.5 , 182.5 , and 365 kN. Surface strain perceptions are read from simulation in Figure 8, where ϵ_{AC_FH1} , ϵ_{BD_FH1} , ϵ_{E_FH1} , and ϵ_{F_FH1} respectively

represent the average strain at A# and C#, B# and D#, and strain at E# and F# under horizontal loading at jack rod 1#. Strain ϵ_{AC_FH2} , ϵ_{BD_FH2} , ϵ_{E_FH2} , and ϵ_{F_FH2} , respectively, denote the strains in horizontal loading at jack rod 2#. Mechanical relation between strains and horizontal load at each jack rod are given in equation (7) as below.

$$\begin{aligned} \epsilon_{AC_FH1} &= C_{AC_FH1} \cdot F_{H1}, & \epsilon_{AC_FH2} &= C_{AC_FH2} \cdot F_{H2}, \\ \epsilon_{BD_FH1} &= C_{BD_FH1} \cdot F_{H1}, & \epsilon_{BD_FH2} &= C_{BD_FH2} \cdot F_{H2}, \\ \epsilon_{E_FH1} &= C_{E_FH1} \cdot F_{H1}, & \epsilon_{E_FH2} &= C_{E_FH2} \cdot F_{H2}, \\ \epsilon_{F_FH1} &= C_{F_FH1} \cdot F_{H1}, & \epsilon_{F_FH2} &= C_{F_FH2} \cdot F_{H2}, \end{aligned} \quad (7)$$

where C_{AC_FH1} and C_{AC_FH2} denote the coefficients between average strain at A# and C# and loading at jack rods 1# and 2#, respectively ($C_{AC_FH1} = -0.0583 \mu\epsilon \cdot kN^{-1}$ and $C_{AC_FH2} = 0.0612 \mu\epsilon \cdot kN^{-1}$). C_{BD_FH1} and C_{BD_FH2} denote the coefficients between average strain of B# and D# and loading at jack rods 1# and 2#, respectively ($C_{BD_FH1} = -0.0612 \mu\epsilon \cdot kN^{-1}$ and $C_{BD_FH2} = 0.0583 \mu\epsilon \cdot kN^{-1}$). C_{E_FH1} and C_{E_FH2} denote the coefficients between the average strain at E# and loading at jack rods 1# and 2#, respectively ($C_{E_FH1} = 1.1814 \mu\epsilon \cdot kN^{-1}$ and $C_{E_FH2} = 1.2242 \mu\epsilon \cdot kN^{-1}$). C_{F_FH1} and C_{F_FH2} denote the coefficients between average strain at F# and loading at jack rods 1# and 2#, respectively ($C_{F_FH1} = -1.2242 \mu\epsilon \cdot kN^{-1}$ and $C_{F_FH2} = -1.1814 \mu\epsilon \cdot kN^{-1}$).

Above mechanical relation reveals that the strains at E# and F# describe the same response in loading at jack rods 1# and 2# despite a slight difference due to strain perception direction and loading location, while strains at A#, C# and B#, D# follow an anti-symmetric change in loading at different jack rods. It can also be observed that the strain response at loading bottoms is far less sensitive in horizontal loading than at the weld base roots, because horizontal loading induces bending effect on the weld bases mainly as cantilever beams.

2.2.3 Coupled loading

In reality, both longitudinal and horizontal forces occur on the two jack rods when the train is running in acceleration, deceleration, or curves. The actual strain at the six perception locations consists of the strains induced by horizontal and longitudinal forces individually on each jack rod. Combining the strains induced by each individual load, the resultant strain under coupled loading can be given by equation (8) as below.

$$\begin{aligned} \epsilon_{AC} &= \epsilon_{AC_FL1} + \epsilon_{AC_FL2} + \epsilon_{AC_FH1} + \epsilon_{AC_FH2}, \\ \epsilon_{BD} &= \epsilon_{BD_FL1} + \epsilon_{BD_FL2} + \epsilon_{BD_FH1} + \epsilon_{BD_FH2}, \\ \epsilon_E &= \epsilon_{E_FL1} + \epsilon_{E_FL2} + \epsilon_{E_FH1} + \epsilon_{E_FH2}, \\ \epsilon_F &= \epsilon_{F_FL1} + \epsilon_{F_FL2} + \epsilon_{F_FH1} + \epsilon_{F_FH2}, \end{aligned} \quad (8)$$

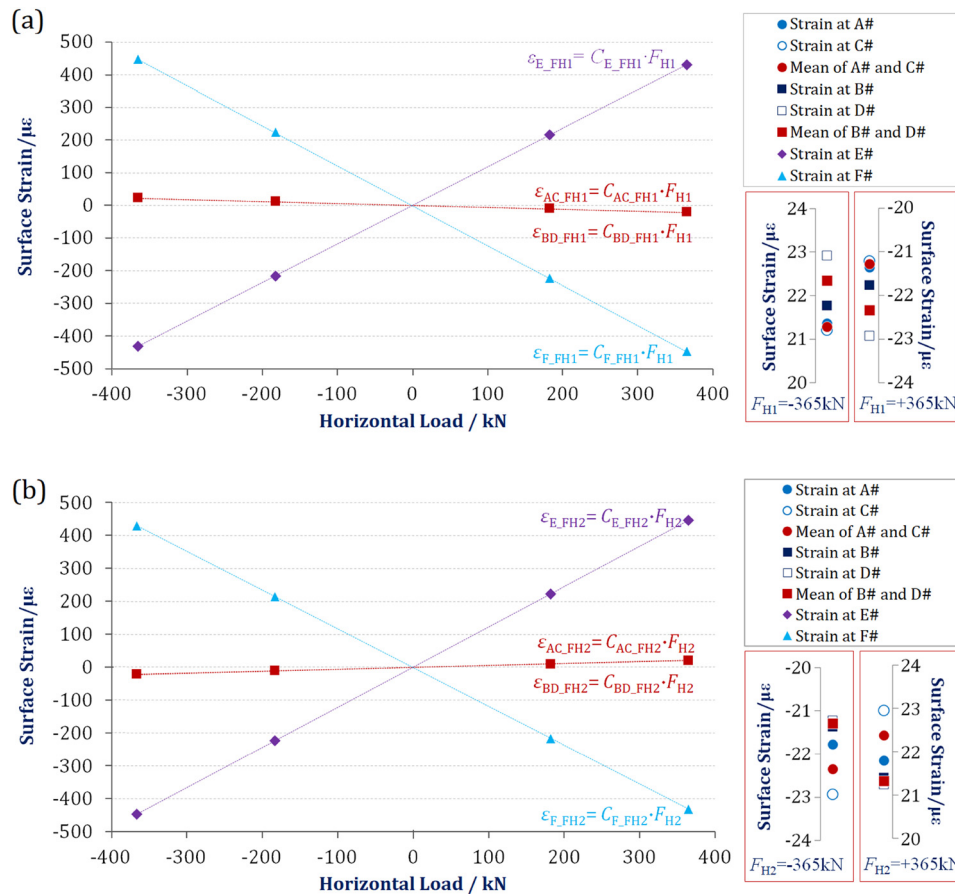


Figure 8: Surface strain response under horizontal loading at individual jack rod: (a) load at jack rod 1# and (b) load at jack rod 2#.

where ϵ_{AC} , ϵ_{BD} , ϵ_E , and ϵ_F denote the resultant average strain of A# and C#, B# and D#, resultant strain at E# and F#, respectively.

Load recognition is given by equation (9) in matrix form from equations (6) to (8) as below.

2.3 Stress calculation

Load identification provides the external load for structural stress calculation. The stress is the 6-component stress at weak locations other than the surface stress used for identi-

$$\begin{Bmatrix} F_{L1} \\ F_{L2} \\ F_{H1} \\ F_{H2} \end{Bmatrix} = \begin{bmatrix} C_{AC_FL1} & C_{AC_FL2} & C_{AC_FH1} & C_{AC_FH2} \\ C_{BD_FL1} & C_{BD_FL2} & C_{BD_FH1} & C_{BD_FH2} \\ C_{E_FL1} & C_{E_FL2} & C_{E_FH1} & C_{E_FH2} \\ C_{F_FL1} & C_{F_FL2} & C_{F_FH1} & C_{F_FH2} \end{bmatrix}^{-1} \cdot \begin{Bmatrix} \epsilon_{AC} \\ \epsilon_{BD} \\ \epsilon_E \\ \epsilon_F \end{Bmatrix}, \quad (9)$$

By measuring the strains at six perception locations, longitudinal and horizontal loads at the two jack rods can be recognized. With the identified loads, structural stress at concentrating areas of longitudinal stop, which might not be feasible for strain measurement, can be calculated via FE simulation for fatigue damage evaluation.

fying the loads. Von Mises (VM) stress is obtained from 6-component stress to form the time-history of structural stress and evaluate the fatigue damage. Maximum stress regions are categorized in four positions, which are determined by reading the maximum equivalent stress in individual load case and coupled load case. Therefore, stress calculation

from identified loads to the structural stress at weak locations can be given in equation (10) as below.

$$\begin{Bmatrix} \sigma_x^{(i)} \\ \sigma_y^{(i)} \\ \sigma_z^{(i)} \\ \tau_{xy}^{(i)} \\ \tau_{yz}^{(i)} \\ \tau_{xz}^{(i)} \end{Bmatrix} = \begin{bmatrix} C_{xx_FL1}^{(i)} & C_{xx_FL2}^{(i)} & C_{xx_FH1}^{(i)} & C_{xx_FH2}^{(i)} \\ C_{yy_FL1}^{(i)} & C_{yy_FL2}^{(i)} & C_{yy_FH1}^{(i)} & C_{yy_FH2}^{(i)} \\ C_{zz_FL1}^{(i)} & C_{zz_FL2}^{(i)} & C_{zz_FH1}^{(i)} & C_{zz_FH2}^{(i)} \\ C_{xy_FL1}^{(i)} & C_{xy_FL2}^{(i)} & C_{xy_FH1}^{(i)} & C_{xy_FH2}^{(i)} \\ C_{yz_FL1}^{(i)} & C_{yz_FL2}^{(i)} & C_{yz_FH1}^{(i)} & C_{yz_FH2}^{(i)} \\ C_{xz_FL1}^{(i)} & C_{xz_FL2}^{(i)} & C_{xz_FH1}^{(i)} & C_{xz_FH2}^{(i)} \end{bmatrix} \cdot \begin{Bmatrix} F_{L1} \\ F_{L2} \\ F_{H1} \\ F_{H2} \end{Bmatrix}, \quad (10)$$

where i is maximum stress location numbering, $C_{xx_FL1}^{(i)}$, $C_{yy_FL1}^{(i)}$, $C_{zz_FL1}^{(i)}$, $C_{xy_FL1}^{(i)}$, $C_{yz_FL1}^{(i)}$, and $C_{xz_FL1}^{(i)}$ are the coefficients between the longitudinal force at jack rod 1# and the 6-component stress. $C_{xx_FL2}^{(i)}$, $C_{yy_FL2}^{(i)}$, $C_{zz_FL2}^{(i)}$, $C_{xy_FL2}^{(i)}$, $C_{yz_FL2}^{(i)}$, and $C_{xz_FL2}^{(i)}$ are the coefficients between the longitudinal force at jack rod 2# and the 6-component stress. $C_{xx_FH1}^{(i)}$, $C_{yy_FH1}^{(i)}$, $C_{zz_FH1}^{(i)}$, $C_{xy_FH1}^{(i)}$, $C_{yz_FH1}^{(i)}$, and $C_{xz_FH1}^{(i)}$ are the coefficients between the horizontal force at jack rod 1# and the 6-component stress. $C_{xx_FH2}^{(i)}$, $C_{yy_FH2}^{(i)}$, $C_{zz_FH2}^{(i)}$, $C_{xy_FH2}^{(i)}$, $C_{yz_FH2}^{(i)}$, and $C_{xz_FH2}^{(i)}$ are the coefficients between horizontal force at jack rod 2#. The structural stress is only caused by dynamic force, excluding the structural pre-stress due to stop pre-tightening.

The standard VM stress is used for fatigue stress calculation as equation (11).

$$\sigma_{vm}^{(i)} = \sqrt{\frac{1}{2}[(\sigma_x^{(i)} - \sigma_y^{(i)})^2 + (\sigma_y^{(i)} - \sigma_z^{(i)})^2 + (\sigma_x^{(i)} - \sigma_z^{(i)})^2] + 6(\tau_{xy}^{(i)2} + \tau_{yz}^{(i)2} + \tau_{xz}^{(i)2})} \quad (11)$$

The range acquired from above does not include any potentially negative part of the stress cycle. The SVM is thus used as the stress calculation rule in equation (12).

$$\sigma_{svm}^{(i)} = \text{sign}(I_1^{(i)}) \cdot \sigma_{vm}^{(i)}, \quad (12)$$

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

In pure longitudinal and horizontal loading, the mechanical relation is formulated between external loads and VM stress at weak locations. The weld bases, where maximum VM stress occurs in longitudinal loading, are denoted on the left side as “WB1#” and on the right as “WB2#”. While in horizontal loading, the maximum VM stress occurs at the

connection root of jack rods and the main stop, which are denoted as “JR1#” and “JR2#” on the left and right side, respectively, as shown in Figure 9.

After running the simulation defined the same as in load identification, the 6-component stresses are read at critical locations including JR1#, JR2#, WB1#, and WB2#. A linear relation is formulated between external loads and individual stress. The calculation coefficients are rounded off to five decimal places to ensure adequate precision, as listed in Table 2.

Calculation results reveal a symmetric rule between the longitudinal loading at jack rod 1# and jack rod 2#, an anti-symmetric rule between horizontal loading at two rods because of geometry and loading symmetry. Calculation coefficients act as inputs in transforming the identified loads to 6-component stress at the 4 critical locations (as the nodes in FEA), and SVM stress time-history for rain-flow counting.

3 Methodology validation

3.1 Numerical simulation

In simulation validation, the FE model and boundary conditions remain the same as in theoretical modeling, and ten random load cases were simulated for each of the four loads at the jack rods. The longitudinal force varies from 0 to 1107.94 kN. The horizontal force changes from −365.7 to 365.7 kN.

In each load case, surface strains at perception locations A#–F# are read into the load recognition model as in equation (9). The identified longitudinal and horizontal load magnitudes (denoted as ID) are contrasted with the randomly given loads (GV) in Table 3. Deviation between the identified and given load at two jack rods ($|ID - GV|$) are taken and plotted as shown in Figure 10.

Validation results indicate that the maximum deviation varies within 2.5 kN. The relative deviation with respect to the given load is $|ID - GV|/|GV| \cdot 100\%$, the maximum does not exceed 4.07, 1.73, 3.21, and 1.63% for longitudinal load at rod 1# and rod 2#, and horizontal load at rod 1# and 2#, respectively. Maximum occurs on

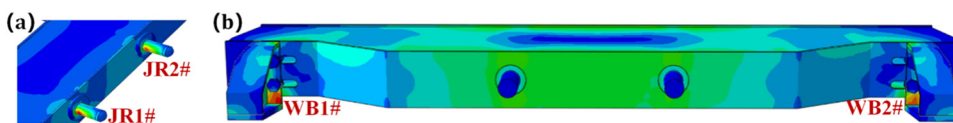


Figure 9: Critical locations in longitudinal and horizontal loading: (a) JR1# and JR2# in horizontal loading and (b) WB1# and WB2# in longitudinal loading.

Table 2: Calculation coefficient between 6-component stress and external loads (MPa·kN⁻¹)

Location	Loads	6-Component stress					
		$C_{xx} (\sigma_x)$	$C_{yy} (\sigma_y)$	$C_{zz} (\sigma_z)$	$C_{xy} (\tau_{xy})$	$C_{yz} (\tau_{yz})$	$C_{xz} (\tau_{xz})$
Weld base 1# (WB1#)	F_{L1}	-0.00288	-0.00018	-0.00291	-0.00023	0.00029	0.00001
	F_{L2}	-0.02201	-0.01676	-0.03592	0	-0.01186	-0.00004
	F_{H1}	0.00566	0.00322	0.00662	0.0008	0.00199	0.00021
	F_{H2}	-0.13341	-0.1827	-1.04409	0.0011	-0.07504	0.00124
Weld base 2# (WB2#)	F_{L1}	-0.02201	-0.01676	-0.03592	0	-0.01186	0.00004
	F_{L2}	-0.00288	-0.00018	-0.00291	-0.00023	0.00029	-0.00001
	F_{H1}	0.13341	0.1827	1.04409	-0.0011	-0.07504	0.00124
	F_{H2}	-0.00566	-0.00322	-0.00662	-0.0008	0.00199	0.00021
Jack rod 1# (JR1#)	F_{L1}	-0.00102	0.04733	-0.03548	-0.00057	0.00426	0.03539
	F_{L2}	0.00129	0.09436	-0.05658	0.00851	0.00544	0.05517
	F_{H1}	0.02483	-0.25056	0.00467	0.10629	-0.02226	0.05521
	F_{H2}	0.02523	-0.23296	-0.01415	0.1133	-0.02117	0.07793
Jack rod 2# (JR2#)	F_{L1}	0.00129	0.09436	-0.05658	0.00851	0.00544	-0.05517
	F_{L2}	-0.00102	0.04733	-0.03548	-0.00057	0.00426	-0.03539
	F_{H1}	-0.02523	0.23296	0.01415	-0.1133	-0.02117	0.07793
	F_{H2}	-0.02483	0.25056	-0.00467	-0.10629	-0.02226	0.05521

Table 3: Comparison between identified and given loads in simulation validation

Load case	Strain perception/ $\mu\epsilon$				Longitudinal load/kN				Horizontal load/kN			
	ϵ_{AC}	ϵ_{BD}	ϵ_E	ϵ_F	F_{L1}		F_{L2}		F_{H1}		F_{H2}	
					ID	GV	ID	GV	ID	GV	ID	GV
LC1#	754	739	1,630	808	858.1	859.9	913.3	913.2	63.7	65.3	277.1	276.7
LC2#	421	619	1,063	610	980.4	979.6	229.3	229.1	-57.3	-59.2	262.2	261.2
LC3#	414	399	34	1,323	464.5	464.4	526.5	524.2	-238.5	-237.1	-298.8	-300.5
LC4#	435	446	955	433	520.6	521.0	477.6	475.5	-117.5	-119.3	335.1	334.9
LC5#	614	392	759	803	138.4	140.6	980.7	979.9	-348.8	-349.6	311.9	311.5
LC6#	796	658	1,225	1,109	583.1	581.7	1104.5	1102.7	-216.7	-215.9	253.7	251.2
LC7#	211	118	348	225	35.8	34.4	387.8	387.7	115.4	117.1	-72.2	-73.4
LC8#	560	427	-41	1,677	341.7	340.3	851.4	849.0	-358.5	-359.4	-366.8	-364.4
LC9#	284	384	813	304	598.6	597.5	218.3	217.9	147.8	147.4	72.5	73.5
LC10#	133	172	314	144	236.4	235.7	88.0	86.5	-118.6	-116.2	192.5	191.6

Note: ID denotes 'Identified'. GV denotes 'Given', which is given by $1,107.94 \text{ kN} \cdot \text{rand}()$ for longitudinal load, and $365.7 \text{ kN} \cdot [1-2 \cdot \text{rand}()]$ for horizontal load, where the random function $\text{rand}()$ varies from 0.0 to 1.0. LC is short for load case.

the loads given with low magnitude, which is dependent on the load magnitude. If the given load approximates to 0 kN, the relative deviation becomes infinite. Hence, the identification precision is evaluated by the ratio of maximum deviation to the average of absolute given loads in all load cases. In this way, the identification precision varies within 1.05% for all load cases, which shows a good consistency with the numerical simulation.

3.2 On-site loading experiment

When the transformer is loaded, two load-carrying beams are adjusted to 3,800 mm. The loaded transformer weighs 3,290 kN, the support distance of which is 6,650 mm in its length. The geometric center of the loading frame coincides with the transformer gravity center in horizontal and lateral directions, as shown in Figure 11. For strain

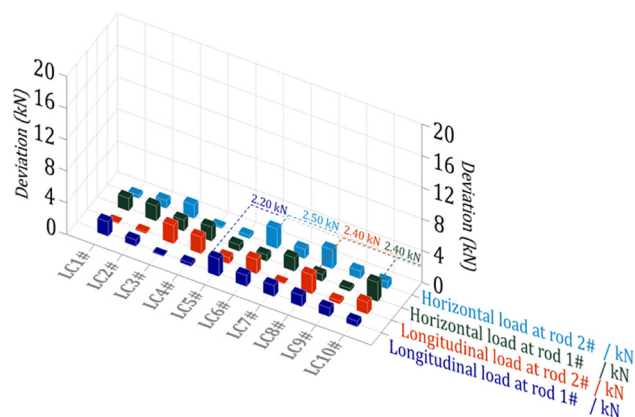


Figure 10: Deviation between identified and given load.

measurement, the arrangement of strain gauges is in a full Wheatstone bridge, three of which are bonded on a dummy block that has the same material as the longitudinal stop. To compensate for ambient temperature drift, it is located beside the strain measuring point, which is shown in Figure 12.

The experimental validation is conducted in longitudinal loading at the two jack rods because of the difficulty

in horizontal loading. Loading magnitude is adjusted by different tightening torque on the bolts. The torque limit on each rod is 2,000 N-m, giving tightening force of 111.1 kN. To account for different load cases, the torque is set in equal and biased magnitudes on each rod. In each load case, the longitudinal load is given by the theoretical relation between tightening torque and force (denoted as GV).

Strains are read from IMC data acquisition (DAQ) system and substituted into the recognition model in equation (9), from which the longitudinal loads are compared with the given loads in as shown in Table 4.

The identified longitudinal and horizontal load magnitudes are compared with the given loads based on the torque in Figure 13, in which the deviation is given as $|ID - GV|$. Calculations reveal that the maximum deviation between the experiment and identification does not exceed 3.9 kN, which is greater than simulation validation (2.5 kN). Errors mainly come from the precision of tightening force and location of strain perceptions. The relative deviation is 3.5%, which is acceptable considering the maximum pre-tightening loads of 111.1 kN.

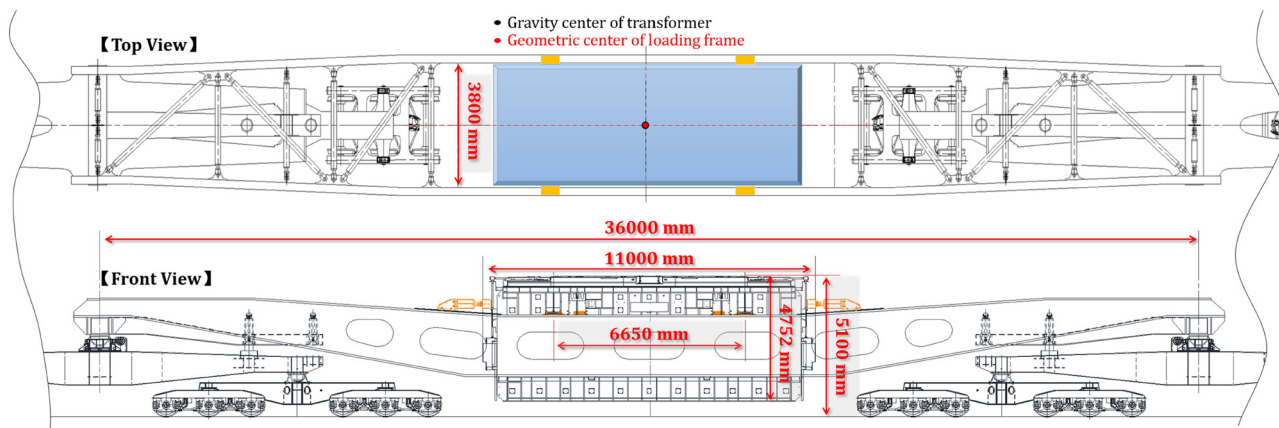


Figure 11: The frame structure and loading dimension for transformer.

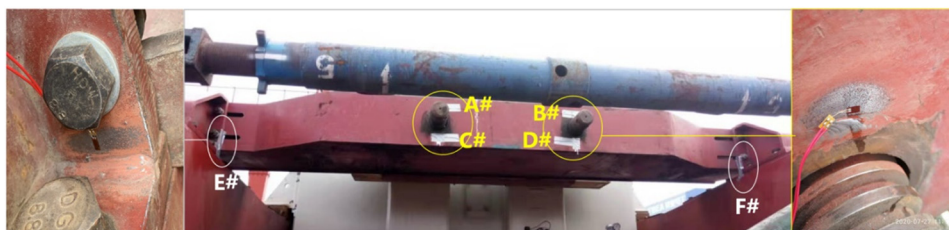


Figure 12: Strain measurement on longitudinal stop.

Table 4: Comparison between identified and given loads in loading experiment

Load case	Strain perception/ $\mu\epsilon$				Longitudinal load/kN				Horizontal load/kN			
	ϵ_{AC}	ϵ_{BD}	ϵ_E	ϵ_F	F_{L1}		F_{L2}		F_{H1}		F_{H2}	
					ID	GV	ID	GV	ID	GV	ID	GV
LC1#	90	89	145	152	107.2	111.1	109.6	111.1	-0.4	0.0	-2.5	0.0
LC2#	45	45	71	77	52.9	55.6	54.9	55.6	-3.5	0.0	0.9	0.0
LC3#	51	72	99	104	113.5	111.1	34.8	37.0	-1.0	0.0	0.8	0.0
LC4#	70	52	103	99	38.9	37.0	108.6	111.1	-1.4	0.0	1.3	0.0
LC5#	63	75	108	119	107.2	111.1	58.8	55.6	-3.4	0.0	-0.2	0.0
LC6#	78	63	116	118	57.9	55.6	112.6	111.1	0.0	0.0	-1.8	0.0

Note: LC1# and LC2# are of the equal loading case, LC3# and LC4# are of the bias loading case in the ratios of 3:1 and 1:3, LC5# and LC6# are of the bias loading case in the ratios of 2:1 and 1:2, respectively.

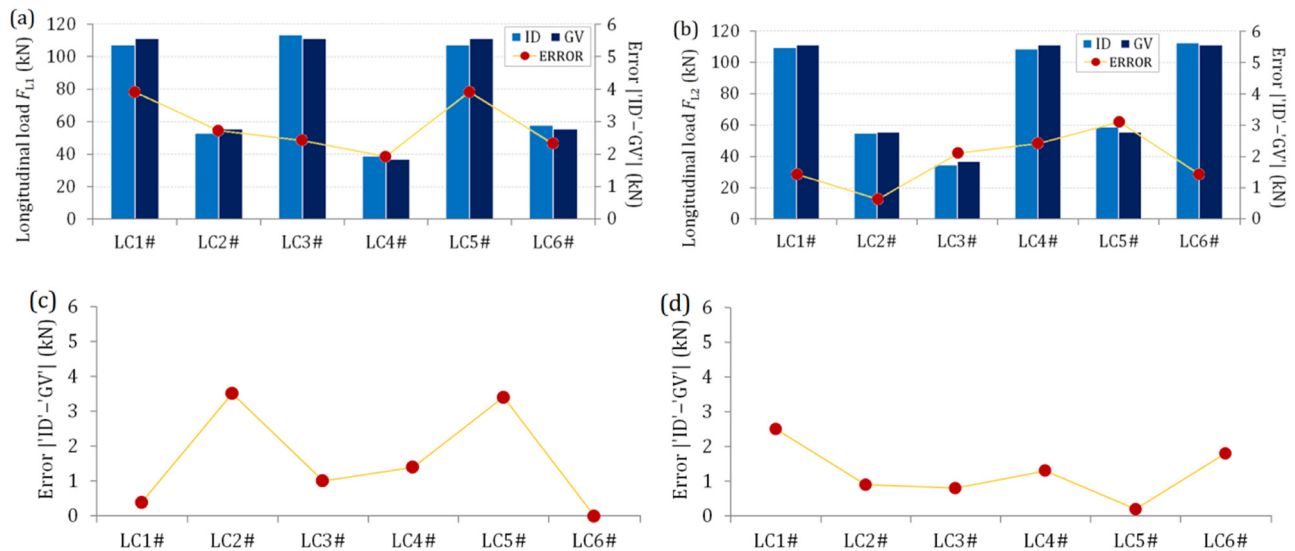


Figure 13: Deviation of identified and given loads in experimental loading: (a) longitudinal load at jack rod 1#; (b) longitudinal load at jack rod 2#; (c) horizontal load at jack rod 1# and (d) horizontal load at jack rod 2#.

4 Application and evaluation

4.1 Transport overview

Vehicle test was conducted on a 3,080 km railway freight line starting from Shaling station on 30 July 2020 to Shuangzhai station on 12 August 2020. For loaded train, the operating speed does not exceed $50 \text{ km} \cdot \text{h}^{-1}$ on different line curves due to its large centrifugal forces. The special train for transformer transport when passing through a station is shown in Figure 14.

The longitudinal stop ahead in that running direction is investigated in the vehicle test. Dynamic strain signal was collected by IMC DAQ system at 256 Hz, and analyzed

with low-pass filtering at 40 Hz [29]. Running mileage is calculated with the running speed (detected by GPS and Stalker-S3 velocimeter) and time interval to describe the train location, and is updated with the railway odometer to eliminate location errors. Other details such as super-elevation, line curve radius, and mileage location were acquired from railway administration, to analyze monitoring results.

4.2 Results and discussion

A mileage history of dynamic strain curve at six strain perceptions is given in Figure 15(a). The detected strain



Figure 14: The freight train with transformer transport from Shaling to Shuangzhai.

reaches $201\ \mu\epsilon$, $181\ \mu\epsilon$, $82\ \mu\epsilon$, and $110\ \mu\epsilon$ as maximum, and $-192\ \mu\epsilon$, $-203\ \mu\epsilon$, $-113\ \mu\epsilon$, and $-36\ \mu\epsilon$ as minimum for points E#, F#, mean of A# and C#, and mean of B# and D#, respectively. By substituting the real-time strain perceptions in equation (7), longitudinal and horizontal loads at the two jack rods can be acquired, as shown in Figure 15(b). The maximum longitudinal load on the jack rod is $162.2\ \text{kN}$ and $157.8\ \text{kN}$ at left and right, respectively, when the train decelerates from 36.8 to $3.6\ \text{km}\cdot\text{h}^{-1}$ within $31\ \text{s}$, while the minimum is -84.5 and $-73.1\ \text{kN}$, respectively, at left and right rods when the train accelerates from 0 to $40\ \text{km}\cdot\text{h}^{-1}$ within $90\ \text{s}$. The horizontal

load occurs when the train is running on the railway line curves. The maximum horizontal load reaches 41.6 and $35.6\ \text{kN}$, respectively, at left and right rods when the train runs at $10\ \text{km}\cdot\text{h}^{-1}$ on a $300\ \text{m}$ radius line curve. The minimum peak comes to -43.4 and $-31.6\ \text{kN}$ at left and right rods when the train runs at $15\ \text{km}\cdot\text{h}^{-1}$ on a $260\ \text{m}$ radius line curve, as shown in Figure 15(b). The reconstructed equivalent stress at weld bases (WB1# and WB2#) and jack rods (JR1# and JR2#) is depicted in Figure 15(c), where the peak stress reaches a maximum of 103.6 , 107.1 , 51.8 , and $45.8\ \text{MPa}$, respectively, for the left weld base (WB1#), right weld base (WB2#), left jack rod (JR1#), and right jack rod (JR2#). And the minimum peak stress goes to -102.9 , -88.9 , -44.1 , and $-56.1\ \text{MPa}$, respectively.

It is revealed from Figure 15 that the identified longitudinal load follows the same trend on both jack rods due to the overall acceleration or deceleration in running direction. Since the instrumented longitudinal stop is at the head in running direction, positive longitudinal load occurs to prevent the transformer from sliding forward when the train decelerates. Accordingly, negative longitudinal load arises due to the relief in transformer sliding backward when the train accelerates. It is also seen that the horizontal load on the two rods goes in the same direction when the train runs on line curves, because

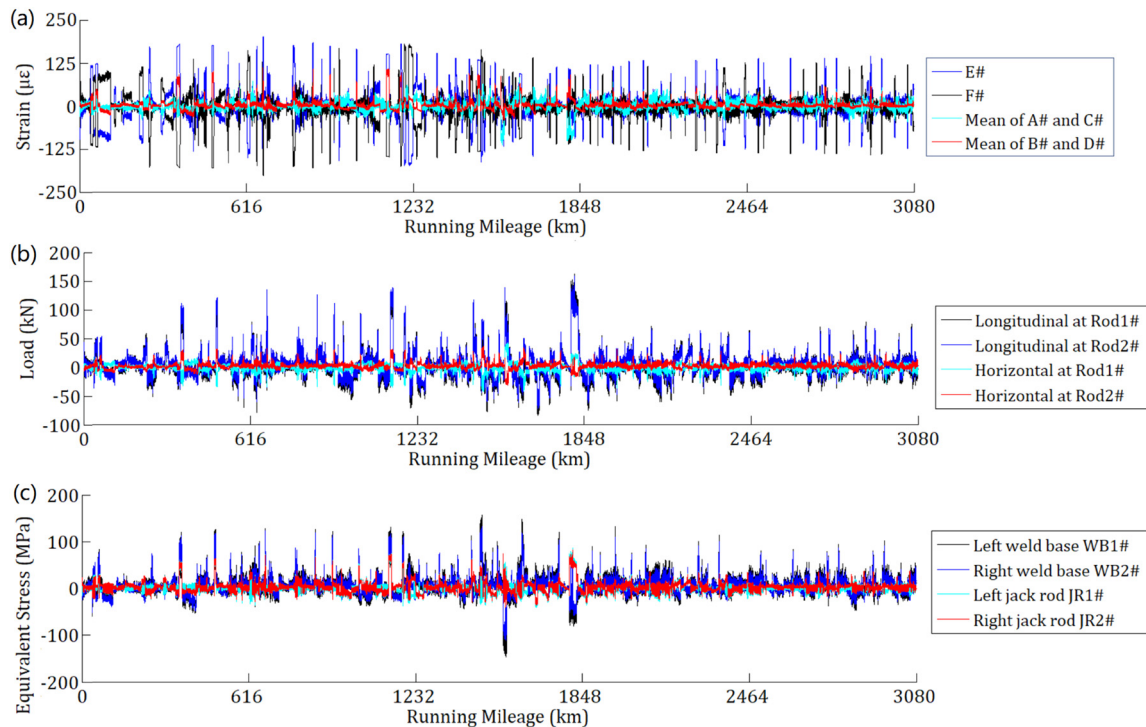


Figure 15: Mileage history of strain perception, identified load, and reconstructed stress: (a) surface strain; (b) identified load and (c) reconstructed stress.

the two jack rods work in cooperation to stop the transformer from sliding horizontally.

To better understand the relation between stop loads and running speed, acceleration is calculated by differentiating the train's running speed. The scattering diagram is given between longitudinal loads and running acceleration in Figure 16. A linear relation is observed from fitting results, where positive acceleration results in a relief in longitudinal loading and negative deceleration induces an increase in longitudinal forces.

Horizontal load occurs on line curves because of the centrifugal inertia force from the loaded transformer. Back to the centrifugal force calculation when an object is moving on circle, the inertial force is proportional to the object mass, the second grade of moving speed, and inversely proportional to curve radius. Hence, the centrifugal acceleration, which is calculated in equation (13) as below, is taken into account as an influential factor affecting the horizontal force.

$$J_{\text{CTRF}} = v_{\text{TR}}^2/R, \quad (13)$$

where v_{TR} is the train's speed, and R is the curve radius. The sign of centrifugal acceleration J_{CTRF} is dependent on the direction of the line curve.

In this way, the scatter diagram between horizontal load at two jack rods and the centrifugal acceleration is given in Figure 17. A linear correlation can be observed in fitting results, which proves that smaller curve radius and higher running speed bring about greater horizontal forces. In addition, running speed variation in curves produces longitudinal forces in small magnitude, but not as large as that during starting acceleration and stopping deceleration on straight lines.

4.3 Fatigue evaluation

Fatigue damage is accordingly analyzed with different spectra groups for convergence, which is derived from the resulting stress mileage history on identified jack rod loads. Recommended spectra grade is given for structural damage evaluation in over-limit freight transport.

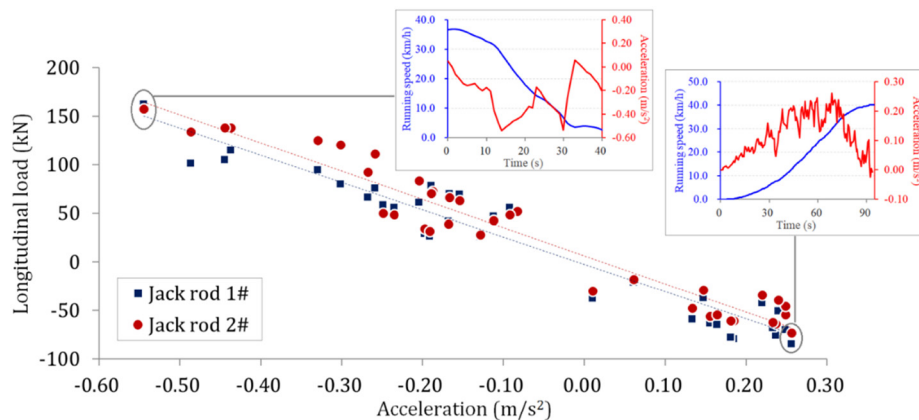


Figure 16: Mechanical relation between longitudinal load and running acceleration.

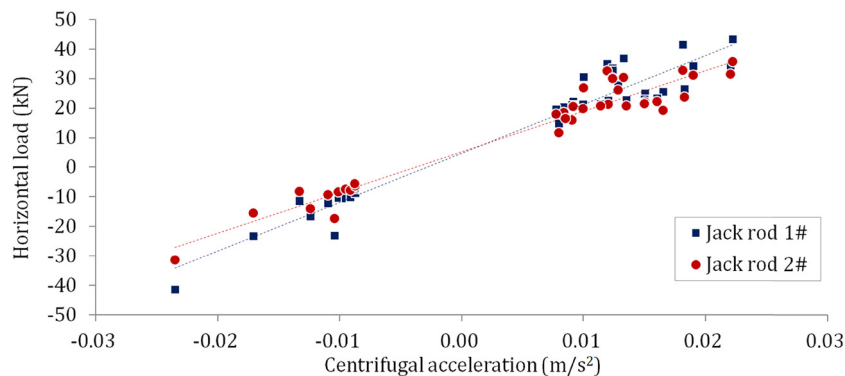


Figure 17: Mechanical relation between horizontal load and centrifugal acceleration.

According to the historical statistical data of freight transport in the past 3 years, fatigue damage at the 4 weak locations are evaluated and extended to the full life cycle.

4.3.1 Theoretical foundation

Before fatigue damage evaluation, based on the rain-flow counting method, time domain-based methods are employed. The reconstructed equivalent stress history is simplified into several load cycles according to the groups in amplitude and mean stress, namely, 2D load spectra. In fatigue damage evaluation, the basic equation of $S-N$ curve is

$$S^m \cdot N = C, \quad (14)$$

where S is the amplitude stress (MPa), and N is the cycle counts to failure. For the HG70 steel material of longitudinal stop, $m = 7.436$ and $C = 5.58 \times 10^{23}$ [30].

To precisely estimate the damage contribution of asymmetric loading, the symmetrical cyclic stress, a mechanical relationship between amplitude stress S_a and mean stress S_m , is given in equation (15) as below.

$$S_{a_EQV} = \frac{S_{ys}}{S_{ys} - S_m} \cdot S_a, \quad (15)$$

where S_{ys} denotes the yield strength of the longitudinal stop structure, $S_{ys} = 345$ MPa.

The transferred equivalent stress amplitude is updated in 2D load spectra, combined with load cycles acquired from rain-flow counting to calculate the fatigue damage. The total fatigue damage is calculated based on Miner's damage accumulation rule, which helps to relate the loading cycles and fatigue strength as below.

$$D = \sum_{i=1}^n \sum_{j=1}^n \frac{N_{ij} \cdot S_{a_EQV_ij}^m}{C}, \quad (16)$$

where N_{ij} and $S_{a_EQV_ij}$ are the load cycle counts and symmetrical equivalent stress at amplitude load of grade i and mean load of grade j , respectively, and n is the load spectra grade number.

4.3.2 Full life mileage calculation

In railway freight transport, well-hole car does not run full day and continuously an entire week. Hence, operating mileage of all 12 DK₃₆-type well-hole freight trains in operation are statistically counted in the past 3 years from 2018 to 2020. The bar

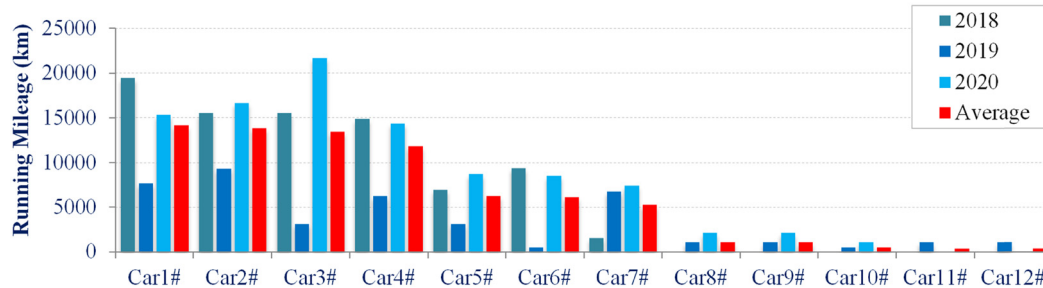


Figure 18: Running mileage histogram of DK₃₆-type well-hole car in past 3 years.

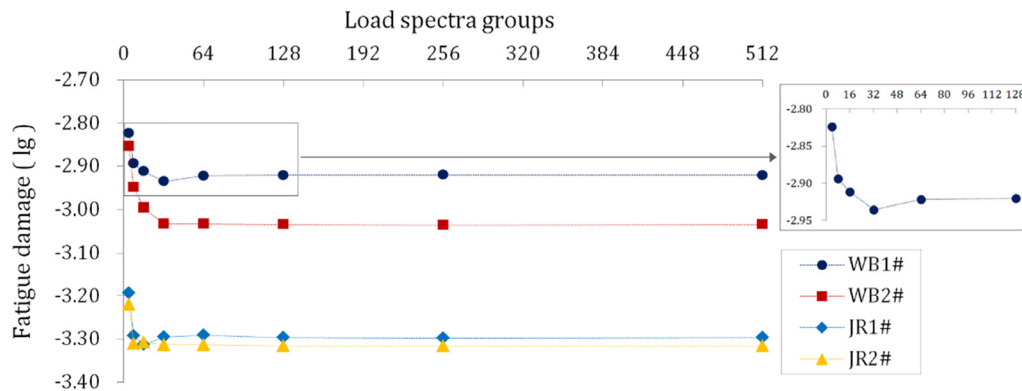


Figure 19: Fatigue damage convergence with load spectra groups.

chart of transporting mileage in each year for each car as well as corresponding average mileage is shown in Figure 18.

From statistics given in Figure 18, the maximum annual and average running mileage of DK₃₆-type well-

hole car is 21,710 and 14,164 km, respectively. The full life design of well-hole car is 30 years, the full life mileage is then 651,300 and 424,920 km, respectively, in terms of annual maximum and average maximum for all cars. In

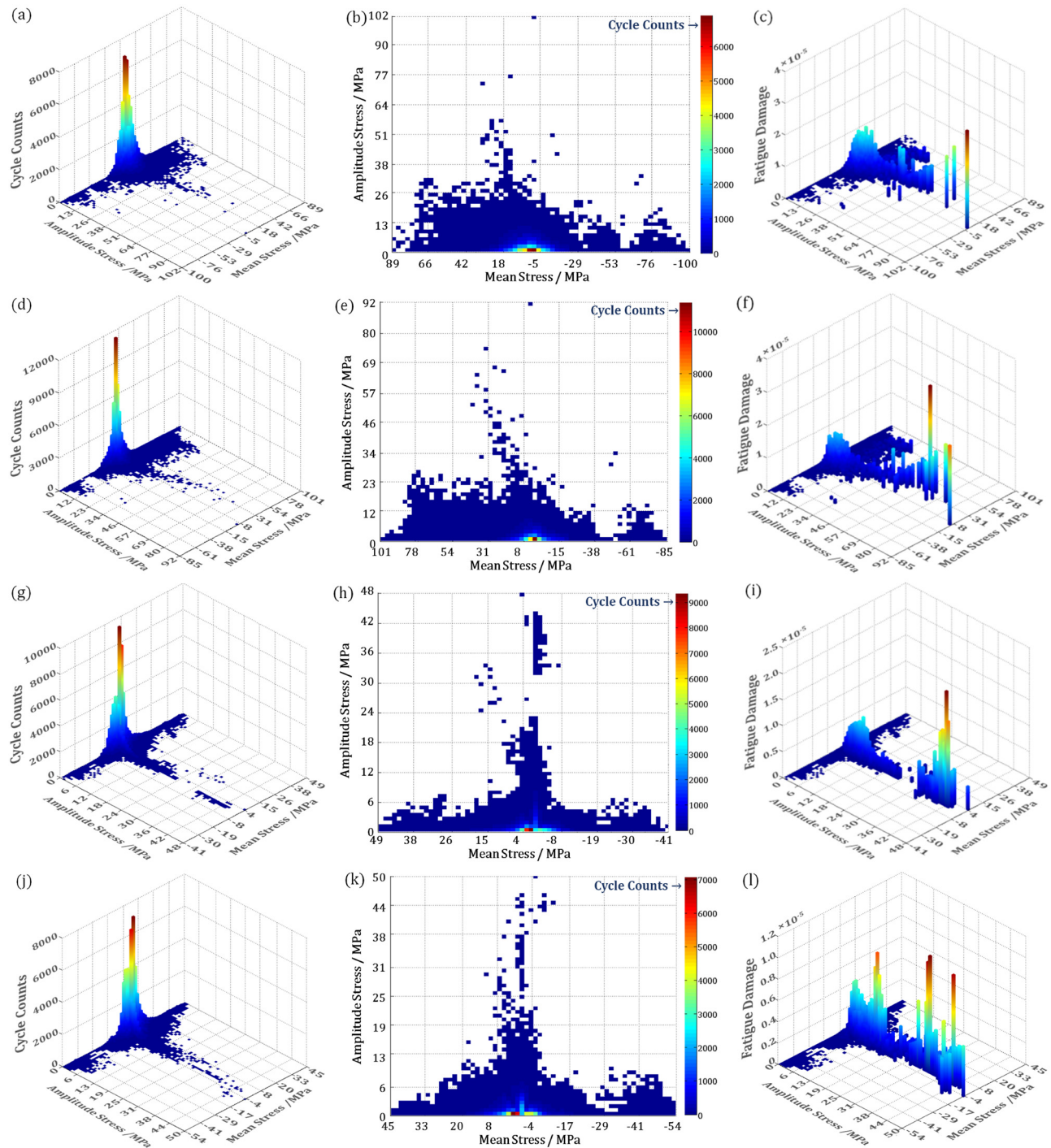


Figure 20: Contour map of 64-grade load and damage spectra at weak locations: (a) load spectra at WB1#; (b) bottom view of load spectra at WB1#; (c) damage spectra at WB1#; (d) load spectra at WB2#; (e) Bottom view of load spectra at WB2#; (f) damage spectra at WB2#; (g) load spectra at JR1#; (h) bottom view of load spectra at JR1#; (i) damage spectra at JR1#; (j) load spectra at JR2#; (k) bottom view of load spectra at JR2# and (l) damage spectra at JR2#.

Table 5: Equivalent fatigue damage in full life mileage for strain perception and weak locations

Equivalency	Strain perception locations				Reconstructed weak locations			
	AC#	BD#	E#	F#	WB1#	WB2#	JR1#	JR2#
EQV_MAX ($C_{EQV_MAX} = 711.4$)	0.156	0.111	0.394	0.261	0.854	0.657	0.359	0.343
EQV_ANU ($C_{EQV_ANU} = 211.5$)	0.046	0.033	0.117	0.078	0.254	0.195	0.107	0.102
EQV_AVG ($C_{EQV_AVG} = 138.0$)	0.030	0.022	0.076	0.051	0.166	0.127	0.070	0.067

Note: EQV_MAX denotes the most unfavorable maximum mileage equivalency, EQV_ANU denotes the statistical annual maximum mileage equivalency, and EQV_AVG denotes the statistical average maximum mileage equivalency.

the following section, the equivalent damage is computed from the damage in practical running mileage and equivalent coefficients. The equivalent coefficient is the ratio of full life to practical running mileage, which are $C_{EQV_ANU} = 211.5$ and $C_{EQV_AVG} = 138.0$, respectively, for annual and average maximum mileage.

Considering the most unfavorable circumstance in which the well-hole car runs constantly as the mileage it has been running in the 14 days during this vehicle test, the equivalent coefficient is calculated as $C_{EQV_MAX} = (30/14) \times 12 \times 30 = 711.4$.

4.3.3 Fatigue life estimation

According to the mean and amplitude stress groups to which the load spectrum belongs, the load cycles are calculated statistically based on the rain-flow counting method. To find the best grade group that can meet the calculation efficiency and precision, 2D fatigue damage is computed from 9-grades distinct groups and converted to base-10 logarithm, as shown in Figure 19.

Calculating results indicate that fatigue damage remains unchanged for WB2#, JR1#, and JR2# from 32 or more groups. However, for weld base WB1#, the convergence starts from the 64 groups. Hence, all evaluations in the following parts are at 64-grade in order to satisfy calculation accuracy and efficiency.

By statistically counting all load cycles via rain-flow counting of the reconstructed equivalent stress, the 3D contour maps are given in terms of load spectra and damage spectra in Figure 20 at the four weak locations, respectively, where the bottom view of load spectra gives the scatter distribution and maximum cycle counts.

As indicated in the contour map, the load cycle counts are similar in the scatter distribution in the two weld bases and the two jack rods. But the distribution appears differently between weld base and jack rod. The maximum cycle count concentrates in low amplitude

stress region where the mean stress approximates zero, where highest cycle counts occur at WB2# and lowest counts happen at WB1#. But large cycle count region is wider at WB1# than at WB2#. For the damage spectra, in a high amplitude stress region, large damage arises above the 40th grade spectra at WB1#, WB2#, and JR1#, while in a wide amplitude stress region, large damage arises above the 24th grade spectra at JR2#.

The evaluated damage of four weak locations, as well as the four strain perception locations, is extended to the full life in 30 years in terms of the most unfavorable maximum, statistical annual, and average maximum mileage. The equivalent fatigue damage is given in Table 5.

It can be observed from the above results that the rating of equivalent damage in descending sequence is the weld base WB1# (0.854), weld base WB2# (0.657), jack rod JR1# (0.359), and jack rod JR2# (0.343) in EQV_MAX equivalency. While in EQV_ANU and EQV_AVG equivalency, which are closer to practical circumstance, the equivalent damage drops to around 30 and 20%, respectively. It is also seen that the equivalent damage at strain measurement locations varies within 32–46% of that at reconstructed weak locations. Although the estimated fatigue damage of measured and reconstructed locations meets the design requirement, they are very close to the safety limit when coming to the most unfavorable case. Hence, a shorter maintenance period is proposed for the weld bases. More attention should be paid to the design, optimization, and inspection at weak locations on longitudinal stops.

5 Conclusion

To sum up, a load recognition model is proposed via multiple strain perceptions on the longitudinal stop structure of the well-hole freight car. The methodology is validated by random loading simulation and on-site loading experiment, and applied in fatigue evaluation on vehicle test. By and large, the conclusions are as follows:

- 1) Load identification for the longitudinal stop is formulated by the mechanical relationship between strain responses at sensitive locations and pure longitudinal, horizontal loading at the individual jack rod. In validation, relative load deviation between the proposed model in random loading simulation and loading experiment suggests good agreement in the range of no more than 4.07%.
- 2) Vehicle test gives an extreme strain perception of $-203\ \mu\epsilon$ at the weld base, longitudinal and horizontal load identification of 162.2 and $-43.4\ \text{kN}$ at jack rods when decelerating from $36.8\ \text{km}\cdot\text{h}^{-1}$ on straight line and passing by 260 m radius line curve at the speed of $15\ \text{km}\cdot\text{h}^{-1}$, respectively. A linear relation is observed between the longitudinal loads and running acceleration, as well as between horizontal loads and the centrifugal acceleration.
- 3) Fatigue damage is calculated on the SVM stress load spectra in different groups via rain-flow counting and Miner's damage accumulation rule. The convergent 64-grade load spectrum is recommended for the fatigue evaluation on well-hole freight car.
- 4) The equivalent damage climbs up to 0.854 on the weld base in the most unfavorable maximum mileage equivalency, whereas, it drops to around 30% and 20%, respectively, in the statistical annual and average maximum mileage equivalency. The equivalent damage at strain perception locations are 32–46% of that at reconstructed weak locations. The design requirements can be satisfied, but the equivalent damage is very close to the safety limit in the most unfavorable case. Therefore, it is recommended to reinforce the defect inspection on weld bases and shorten the maintenance period of the well-hole freight car.

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