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Research on extending the fatigue life of railway steel bridges by using intelligent control

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HIGHLIGHTS

- Optimum multi-scale structural analysis combining shell and solid FE models of a bridge.
- Calculating fatigue life of a steel bridge considering both dynamic and thermal actions.
- Smart vibration control towards optimising fatigue performance of steel bridges.
- Developing a case study application for the Poyang Lake Bridge in China.

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ABSTRACT

This paper investigates the potential of a vibration control-inspired method towards extending the fatigue life of railway steel bridges. Based on coupled thermal-mechanical and vehicle-track analysis, both the residual stresses from welding and these from traffic on the bridge are obtained. Subsequently, a multi-scale approach with a shell Finite Element (FE) model of the whole bridge and a solid FE model of its critical joints is put forward. The equation of motion is established for the controlled bridge, equipped with a Magnetorheological-Tuned Mass Damper (MR-TMD) system, while the combination of excitation, welding and control effects is practiced through own-developed packages and commercial software sub-model routines. The framework is showcased for the study of the Poyang Lake Railway Bridge in China. After obtaining the controlled stress states at the critical welded joint, the fatigue crack initial life is evaluated by using the critical plane method and the linear cumulative damage theory. Simulation results indicate that the multi-scale modelling approach followed, meets the accuracy needs for capturing the cracking process of the welded joint with high computational efficiency. The MR-TMD system, even when moderately reducing the critical joint stress amplitudes, can improve substantially the overall bridge fatigue resistance over the uncontrolled structure.

1. Introduction

Railway steel bridges are very common long span bridges, constituting a large sector of the traffic communication network. Owing to their long time and frequent train traffic, cumulative damage may occur in their welded regions. In particular, stress concentrations can easily be generated under the combined action of multi-axial dynamic-excitation stress and welding-owed residual stress. Such could further lead to fatigue damage that sets off as crack initiation and, in a worst case scenario, could progress to failure of parts of the bridge, putting a serious concern in terms of life cycle design. Collapse and damage of steel bridges caused by cumulative fatigue action have been frequently reported across the world up to this date [1–3]. Therefore, it is important to propose and adopt effective means to prolong the fatigue crack initial life of steel bridge parts; such could subsequently extend the service life of railway steel bridges, and reduce the risk, economic losses and casualties caused by potential damage.

In the past decades, many scholars have carried out considerable theoretical and experimental research in the field of bridge fatigue life assessment. Namely, within the achievements produced in the field one can quote the establishment of fatigue damage models, the study of initial crack mechanisms and the evaluation of a structure's overall fatigue life [4,5]. Li and Chan, for instance, applied continuous damage mechanics to their

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Nomenclature

k_x	the x directional thermal conductivity factors
k_y	the y directional thermal conductivity factors
k_z	the z directional thermal conductivity factors
λ	efficiency of the heat source
U_w	welding voltage
I_w	welding current
$\mathrm{V_H}$	volume of the welding unit
ρ	the parent material density
C	specific heat capacity
T	the joint temperature generated by the welding
t	the independent time variable
N_x	the perpendicular to the boundary of x direction cosines
N_y	the perpendicular to the boundary of y direction cosines
N_z	the perpendicular to the boundary of z direction cosines
h_c	the heat transfer coefficient of convection
h_r	the heat transfer coefficient of radiation
q_s	boundary heat flux
T_r	temperature of radiation
T_∞	surrounding temperature
f_f	the heat source distribution of the double ellipsoid model for front heat source
f_r	the heat source distribution of the double ellipsoid model for rear heat source
q_f	the heat source of the double ellipsoid model for front heat source
q_r	the heat source of the double ellipsoid model for front heat source
v	welding speed
x_0	the x coordinate of the welding initial position
a_1	arc welding parameter
a_2	arc welding parameter
b	arc welding parameter
c	arc welding parameter
$\{d\sigma\}$	vector of stress
$\{d\varepsilon\}$	vector of strain
dT	temperature increment
$[D]$	elastic or elastic-plastic constitutive law matrix
$\{C\}$	temperature dependence vector
M_c	weight of the train car
J_c	inertia of the train car
M_t	weight of bogies
J_t	inertia of bogies
M_{wi}	the wheel's weight
v_{wi}	vertical displacement of each wheel
v_{ti}	vertical displacement of the bogies
φ_{ti}	rotation angle of the bogies
v_c	vertical displacement of the repeating train car
φ_c	rotation of the repeating train car
u_1, u_2	the rail vertical displacements
u_3, u_4	the railway bridge sleeper vertical displacements
u_5, u_6	the ballast vertical displacement
k_{y1}	the elastic coefficients of the fastener
k_{y2}	the elastic coefficients of the ballast
k_{y3}	the elastic coefficients of the railway bridge sleeper
c_{y1}	the damping coefficients of again the fastener
c_{y2}	the damping coefficients of again ballast
c_{y3}	the damping coefficients of again the railway bridge sleeper
$\mathrm{M_v}$	the mass matrices of the train
$\mathrm{C_v}$	the damping matrices of the train
$\mathrm{K_v}$	stiffness matrices of the train
$\ddot{\mathrm{a}}_\mathrm{v}$	the acceleration vector
$\dot{\mathrm{a}}_\mathrm{v}$	the velocity vector
$\mathrm{a_v}$	the displacement vector
$\mathrm{Q_V}$	the force vector

$\mathbf{M_l}$	the mass, damping vector of the track
$\mathbf{C_l}$	the damping vector of the track
$\mathrm{K_l}$	the stiffness matrices vector of the track
$\mathrm{Q_l}$	the load vector of the track
e	the element identifier of the 2D track beam
k_H	the equivalent spring stiffness
u_i	the interpolating function of u_1 and u_2 of the nodal displacement
M_C	the mass matrices of the coupled system
$\mathrm{C_C}$	the damping matrices of the coupled system
$\mathrm{K_C}$	the stiffness matrices of the coupled system
$\mathrm{Q_C}$	the load vector
$\mathrm{C_{Vl}}, \mathrm{C_{lV}}$	the coupling damping
Ω	spatial angular frequency variable
Ω_c	the truncated spatial angular frequency of the vertical profile irregularity
Ω_r	the truncated spatial angular frequency of the alignment irregularity
A_v	the high interference roughness coefficient
Z_r, Z	the vertical displacements of the bridge deck and TMD mass respectively
$\ddot{\mathbf{x}}$	the acceleration vector of the bridge discrete model
$\dot{\mathbf{x}}$	the velocity vector of the bridge discrete model
$\mathbf{x}$	the displacement vector of the bridge discrete model
M	the mass matrices
C	the stiffness matrices
K	the damping matrices
H	locator matrix of installed MR-TMD system
F(t)	the external force input
U_{MR-TMD}	the control force vector provided by the MR-TMD system
K_{Ti}	the stiffness properties of the i^{th} TMD in the MR-TMD
C_{Ti}	the damping properties of the i^{th} TMD in the MR-TMD
F_{MRi}	the damping force of the i^{th} MR damper
C_d	the viscous damping coefficient
F_d	the coefficient of controllable Coulomb damping force
K_d	the equivalent axial stiffness of the damper
f_{0i}	the output force deviation caused by the damper accumulator
e_b	the Bingham sliding displacement
C_{ds}	the coefficient of viscous damping of damper on the condition of zero electric field strength
F_{ds}	the coefficient of controllable Coulomb damping force of damper on the condition of zero electric field strength
K_{ds}	the equivalent axial stiffness of damper on the condition of zero electric field strength
C_{dd}	the voltage sensitivity of viscous damping of the damper
F_{dd}	the voltage sensitivity of controllable Coulomb damping force of the damper
K_{dd}	the voltage sensitivity of equivalent axial stiffness of the damper
η	the time coefficient of the damper's magnetic hysteresis response
I	the applied current intensity
u	the internal variable reflecting the relationship between model parameters and current intensity.
$F_{d\max}$	the maximum coefficient
$F_{d\min}$	the minimum coefficient
ξ	the adjustment factor of the Coulomb damping force
ε_x	the x -directional normal strain
ε_y	the y -directional normal strain
ε_z	the z -directional normal strain
ε_{xy}	the xz -directional shear strain
ε_{yz}	the yz -directional shear strain