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Development of an efficient approach for fatigue crack initiation and propagation analysis of bridge critical details using the modal superposition technique

Cláudio S. Horas[a,*], Guilherme Alencar[a], Abílio M.P. De Jesus[b], Rui Calçada[a]

[a] CONSTRUCT-LESE, University of Porto, Faculty of Engineering, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[b] INEGI, University of Porto, Faculty of Engineering, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

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ABSTRACT

The fatigue damage assessment of large bridges is highly conditioned by the required computational high demands. Generally, in order to overcome the multi-scale problem, global and local models are needed to properly account for both global structural behaviour and the local nature of the fatigue damage. The analysis of such structural problems using direct time-integration algorithms is impracticable in most of the cases, which leads to the necessity of developing alternative methodologies in order to increase the computational efficiency and the accuracy of fatigue cracking assessments. In this respect, effective computational algorithms based on the modal superposition technique have been proposed and implemented in previous works. Overall, such workflow considers the interaction between the global and local models combined with the application of the modal stress intensity factor concept. Aiming at performing an efficient and accurate assessment of the fatigue damage, firstly, combining the Fracture Mechanics principles and crack propagation laws, the crack propagation phase in a complex bridge detail is analysed. In this regard, the present paper aims at proposing relevant improvements to the above-mentioned methodology, namely: i) the refinement of the implemented submodelling techniques in order to increase the accuracy of stress and strain fields computation and allow to account for smaller initial crack lengths; ii) the analysis and limitation of the considered number of vibration modes to the relevant ones for the local dynamic response; and iii) the implementation of a parallel computing approach for the calculation of the modal stress intensity factors related to the vibration modes defined in ii). The fatigue assessment procedures were applied to an assumed cracked welded detail of a recent railway composite bowstring bridge located in Portugal. Also, since the assumption of a pre-existing crack may lead to very conservative predictions, the modal superposition technique is further extended to evaluate the fatigue crack initiation phase, demonstrating the safety of the analysed case study in the absence of existing defects.

1. Introduction

The occurrence of important fatigue damages is a relevant issue for the design, maintenance and strengthening of complex structures. In this context, railway bridges are permanently subjected to complex cyclic loadings responsible for global and local dynamic responses which may lead to the development of severe fatigue cracking.

* Corresponding author at: University of Porto, Engineering Faculty, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal.
E-mail address: claudio.silva.horas@fe.up.pt (C.S. Horas).

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Nomenclature

a	crack length (half of the crack length for a central crack)
a_i	initial crack length
a_c	critical crack length
B_n	number of loading blocks
b	cyclic fatigue strength exponent
C	damping matrix
$\bar{C}$	material-dependent factor of the Paris law
c	fatigue ductility exponent
D_T	fatigue damage related to train T
E_c	Young modulus of the concrete
F	nodal forces vector
f_j	nodal force of the jth mode of vibration
K	damping matrix
$\bar{K}$	stress intensity factor
K_c	material toughness
K_j	modal stress intensity factor of the jth mode of vibration
K_{dyn}	stress intensity factor due to the dynamic loading
K_{sta}	stress intensity factor due to the static loading
K_{total}	total stress intensity factor
K_I	stress intensity factor related to mode I
$K_{I,\ sta}$	stress intensity factor related to mode I due to the static loading
$K_{I,\ j}$	modal stress intensity factor of the jth mode of vibration related to mode I
$K_{I,\ jp}$	modal stress intensity factor of the jth mode of vibration related to mode I and n_p
K_{II}	stress intensity factor related to mode II
$K_{II,\ j}$	modal stress intensity factor of the jth mode of vibration related to mode II
$K_{II,\ jp}$	modal stress intensity factor of the jth mode of vibration related to mode II and n_p
$K_{II,\ sta}$	stress intensity factor related to mode II due to the static loading
K_{III}	stress intensity factor related to mode III
$K_{III,\ j}$	modal stress intensity factor of the jth mode of vibration related to mode III
$K_{III,\ sta}$	stress intensity factor related to mode III due to the static loading
K_{eq}	equivalent stress intensity factor
M	mass matrix
$\bar{m}$	material-dependent factor of the Paris law
m_j	modal mass of the jth mode of vibration
$N_{f,\ i}$	necessary number of cycles to the crack initiation related to $\Delta\sigma_i$ and n_i
NoM	number of vibration modes analysed by each process n_p
n_p	number of parallel computing processes
n_i	number of cycles related to $\Delta\sigma_i$ and $N_{f,\ i}$
u	displacement vector
$\dot{u}$	velocity vector
$\ddot{u}$	acceleration vector
w_j	modal frequency of the jth mode of vibration
Y	geometry-dependent stress intensity magnification factor
Y_j	modal coordinates of the jth mode of vibration
Δa	crack increment
Δa_{inc}	constant crack increment
$\Delta\sigma_i$	acting stress range i
$\Delta\sigma_E$	equivalent stress range
$\Delta\sigma_{E,\ I}$	equivalent stress range related to mode I
$\Delta\sigma_{E,\ II}$	equivalent stress range related to mode II
ΔK	stress intensity factor range
$\Delta K_{eq,\ i}$	equivalent stress intensity factor range i
ΔK_{th}	stress intensity factor range threshold
$\Delta K_{I,\ eq}$	equivalent stress intensity factor range related to mode I
$\Delta K_{II,\ eq}$	equivalent stress intensity factor range related to mode II
$\frac{da}{dN}$	crack propagation rate
ξ_j	modal damping coefficient of the jth mode of vibration
θ	kink angle
$\bar{\theta}$	equivalent kink angle
σ	acting nominal stress
σ_i	acting stress i
σ_{dyn}	dynamic stress
σ_j	modal stress related to the jth mode of vibration
σ_f'	cyclic fatigue strength coefficient
σ_m	mean stress related to $\Delta\sigma_i$
ϕ_j	modal displacement field related to the jth mode of vibration
ψ	generic damage parameter
ψ_j	modal damage parameter of the jth mode of vibration
ψ_{sta}	modal damage parameter due to the static loading

Different approaches have been suggested for fatigue assessment, namely stress-life global and local methodologies, notch strain methods and Fracture Mechanics based approaches. In the most important standards and guidelines, the global *S-N* method based on nominal stresses has been suggested to evaluate the complete fatigue life of a certain detail, establishing a relation between the acting nominal stress range and the fatigue life expressed in terms of load cycles [1–3]. Despite the wide use, such approach has important limitations, among them: i) a limited number of connections and simple loading cases, as foreseen in the standards and guidelines, are addressed; ii) the material influence is not accounted for, since the nominal *S-N* curves are considered for a wide range of materials; and iii) no distinction is taken into account between crack initiation and crack propagation phases, which hinders the prediction of the remaining fatigue life of an existing cracked detail. Local stress-life methodologies, notch strain methods and Fracture Mechanics based approaches, isolated or combined, may be used as more precise alternatives to the global *S-N* method. In this respect, aiming at investigating the different phases of the cracking phenomenon, the importance and applicability of the aforementioned methodologies to analyse fatigue issues in large metallic bridges has been increasing [4–9].

The Fracture Mechanics has been developed in order to understand the occurrence of low-stress fracture in high strength materials under cyclic loads [10]. The development of cracks, from the micro-scale phenomenon until the occurrence of a certain failure mode,