ARTICLE IN PRESS

Engineering Fracture Mechanics xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

General cracked-hinge model for simulation of low-cycle damage in cemented beams on soil

Asmus Skar [a,*], Peter Noe Poulsen [b], John Forbes Olesen [b]

[a] *COWI A/S, Parallelvej 2, 2800 Kgs. Lyngby, Denmark*

[b] *Technical University of Denmark, Brovej, Building 118, 2800 Kgs. Lyngby, Denmark*

ARTICLE INFO

Article history:
Received 2 September 2016
Received in revised form 11 January 2017
Accepted 16 January 2017
Available online xxxx

Keywords:
Fracture mechanics
Cohesive crack
Non-linear FEM
Low-cyclic fatigue
Cemented materials
Pavement analysis

ABSTRACT

The need for mechanistic constitutive models to evaluate the complex interaction between concrete crack propagation, geometry and soil foundation in concrete- and composite pavement systems has been recognized. Several models developed are either too complex or designed to solve relatively simple problems, e.g. limited to one type of load configuration or test set-up. In order to develop a general and mechanistic modeling framework for non-linear analysis of low-cycle damage in cemented materials, this paper presents a cracked-hinge model aimed at the analysis of the bending fracture of the cemented material. The model is based on the fracture mechanics concepts of the fictitious crack model. The proposed hinge is described in a general and consistent format, allowing for any type of stress-crack opening relationship and unloading- reloading formulation. The functionality of the proposed hinge model is compared to numerical- and experimental results. The proposed hinge shows good performance and seems promising for the description of low-cycle fracture behavior in cemented materials.

1. Introduction

Concrete- and composite pavement systems are subjected to cyclic loading from vehicles resulting in initiation of bending cracks in the quasi-brittle cemented material. Subsequently, these cracks propagate leading to failure of the pavement structure. The structural design of such pavements is primarily based on empirical formulas which convert the elastic response analysis into a measure of performance [1–3], referred to as the Mechanistic-Empirical (M-E) method. However, such a method cannot account for significant factors influencing the response, e.g. describing the interaction between loads, material properties, geometry and soil foundation in a unified manner.

The limitations of the M-E method and the growth in computer capabilities have resulted in an increasing development of more rational models for pavement analysis during the past decades. That work began in the early 1990s, studying mainly asphalt concrete mixtures in flexible pavements [4–6], reflective cracking in asphalt overlays [7] and permanent deformation of unbound materials [8–10]. These models are typically based on a mechanistic approach using appropriate numerical tools, e.g. the finite element (FE) method. This allows for geometry, inhomogeneities, anisotropy, and nonlinear material properties of all pavement layers to be considered.

Numerical analysis of crack propagation in concrete- and composite pavement systems have primarily carried out applying cohesive zone modeling [11–15]. Gaedicke and Roesler [16,17] applied a cohesive zone model for studying fracture in

* Corresponding author.
E-mail address: asch@cowi.dk (A. Skar).

http://dx.doi.org/10.1016/j.engfracmech.2017.01.016
0013-7944/© 2017 Elsevier Ltd. All rights reserved.

Nomenclature

a_i	slope of tangent line segment on softening curve
a_0	depth of notch
b_i	intersection of the tangent line segment on softening curve and the abscissa
$\mathbf{B}$	strain interpolation matrix
c_1	softening curve model parameters
c_2	softening curve model parameters
$CMOD$	measured crack mouth opening displacement
cp	constitutive point
c	crack-length
d	distance from beam face to measurment point
$\mathbf{D}_t$	hinge tangent stiffness matrix
e_i	lever arm of hinge fiber
E_c	Young's modulus of cemented material
E_d	damaged unloading- reloading stiffness of hinge fiber
f_t	uni-axial tensile strength of cemented material
G_F	fracture energy
h	hinge height
H	beam height
ip	interpolation point
k_1	softening curve model parameters
k_h	horisontal spring stiffness
$\boldsymbol{k}_t$	beam element tangent stiffness matrix
k_v	vertical spring stiffness
L	beam length
L_e	beam element length
M	moment force
N	normal force
$\mathbf{N}$	displacement interpolation matrix
n	number of fibers
P	load
$\boldsymbol{q}$	beam element internal nodal force
s	hinge width
t	hinge thickness
u	elongation of hinge fiber
$\boldsymbol{v}$	element dof vector
w	crack-opening
w_c	zero-stress displacement
w_{k_1}	softening curve model parameters
α_i	monotonic damage parameter
δ	total midspan displacement of beam
δ^{cr}	cracking beam midspan deformation of hinge
δ_g	geometrical amplification
δ^{el}	elastic beam midspan deformation of hinge
δ_e	elastic deformation of specimen
δ_{COD}	the opening due to the presence of the crack
$\bar{\varepsilon}_0$	mean normal strain at beam axis
$\bar{\varepsilon}$	mean normal strain of hinge fiber
ε_{ct}	strain at crack initiation
$\bar{\varepsilon}^{pl}$	mean plastic strain component
$\bar{\varepsilon}^{cr}$	inelastic cracking strain component
η	tensile cyclic damage parameter
$\bar{\varepsilon}_{ult}$	zero-stress strain
$\bar{\varepsilon}^{unl}$	strain during unloading- and reloading
γ	shear coupling spring coefficient
$\bar{\kappa}$	mean curvature of the hinge
μ	normalized moment
σ_u^k	negative intersecting point on abscissa
σ_{ur}	normal cohesive stress during unloading- and reloading of hinge fiber

Please cite this article in press as: Skar A et al. General cracked-hinge model for simulation of low-cycle damage in cemented beams on soil. Engng Fract Mech (2017), http://dx.doi.org/10.1016/j.engfracmech.2017.01.016