Engineering Structures 150 (2017) 256–270

Contents lists available at ScienceDirect

Engineering Structures

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

A refined modelling for thermal-induced upheaval buckling of continuously reinforced concrete pavements

Guotao Yang, Mark A. Bradford *

Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, UNSW Sydney, NSW 2052, Australia

ARTICLE INFO

Article history:
Received 22 April 2017
Revised 1 June 2017
Accepted 2 June 2017

Keywords:
Thermal buckling
Heatwaves
Upheaval buckling
Continuous pavements
Postbuckling
FEM

ABSTRACT

Heatwaves may cause large axial forces to develop in continuous pavements, with potential buckling taking place when the axial force attains a certain value. With the continual evolution of global warming and prolonged heatwaves, upheaval buckling of continuously reinforced concrete pavements has been a documented problem in highway engineering, as it can have catastrophic consequences. This paper conducts a refined modelling of thermal-induced upheaval buckling of concrete pavements within the framework of general finite element codes. The finite element model is developed by considering the stiffness of the pavement subgrade and the friction between the pavement and its base. Two models of concrete pavements are taken into account: one is a continuous pavement and the other a continuous pavement with a joint. In order to trigger the buckling response, an imperfection of the pavement is incorporated and the configuration of the imperfection is taken from an analytical study. Comparisons between the proposed modelling and the test results, as well as a comparison between the numerical model and the analytical model, are given in the paper. The buckling responses of the pavements are investigated parametrically, with the parameters involved being the pavement thickness, base friction, subgrade modulus, imperfection amplitude, pavement weight and pavement stiffness. Based on the extensive numerical analysis, a prediction model for use in the design of continuously reinforced concrete pavements is proposed.

1. Introduction

With the documented evolution of global warming and extreme climate events, upheaval buckling of continuously reinforced concrete pavements has become a problem in highway engineering [1,2]. Even some forty years ago, one hundred and seventy-two upheaval buckles or blowups of various severity were reported during 1975 and 1976 in Ohio, USA [3]. Pavement buckling has the potential to lead to catastrophic incidents [4], causing obvious loss of life and limb as well as large financial ramifications. Therefore, assessments of pavement buckling are of great value to the engineering community in the context of the frequent prolonged heatwaves experienced in many countries around the world [5,6]. Extensive research has been reported on the mechanism of thermal-induced pavement buckling. Kerr and Dallis Jr [7] conducted a postbuckling analysis of pavements by adopting a bilinear approximation for the resistance of the pavement base. Subsequently, a continuous hyperbolic tangent function was employed to represent the interaction behaviour between the pavement and the subgrade [8], based on which a pavement adjoining a rigid structure was analysed and parametric analyses were undertaken [9,10]. Croll [11] discussed the mechanics involved in the upheaval buckling of pavements and described an analysis for their buckling as two separate modes; one was a one-dimensional beam model and the other a two-dimensional plate model, based on a simple buckling representation that does not consider the unbuckled adjoining region. Yang and Bradford [12] proposed an analytical model by considering both the contribution of the adjoining region and the effects of pavement imperfections. However, the influence of the stiffness of the pavement foundation on its thermal buckling appears not to have been investigated hitherto.

When the stiffness of the pavement is taken into account, the pavement can be idealised as a beam on a foundation [13]. Most of the research on this topic has been focused on a beam on a foundation subjected to lateral loading [14–16]. El-Aini [17] investigated the effects of the foundation stiffness on the postbuckling responses of railway tracks, but the bifurcation buckling point could not be obtained. Bifurcation buckling of a weakened beam on a foundation was investigated by Wang [18]. Li and Batra [19] analysed the deformations of pinned-pinned and fixed-fixed Euler-Bernoulli beams supported on nonlinear elastic foundations and heated uniformly into the postbuckling regime, in which

---

* Corresponding author.
E-mail addresses: guotao.yang@unsw.edu.au (G. Yang), m.bradford@unsw.edu.au (M.A. Bradford).

http://dx.doi.org/10.1016/j.engstruct.2017.06.005
0141-0296/© 2017 Elsevier Ltd. All rights reserved.

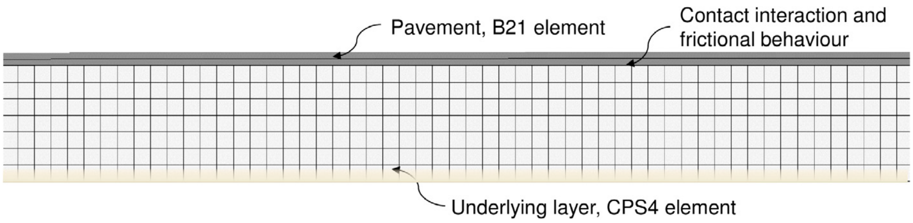


Fig. 1. Finite element model of a pavement.

Table 1
Parameters for the interaction between the pavement and the base.

Base	μ (h = 100 mm)	μ (h = 200 mm)	μ (h = 300 mm)	Elastic slip γ (mm)
Lean Concrete	1.0536	0.6215	0.4775	0.91551
Crushed Stone	3.4480	2.0339	1.5625	0.61034
Asphalt	7.1834	4.2373	3.2553	0.45776

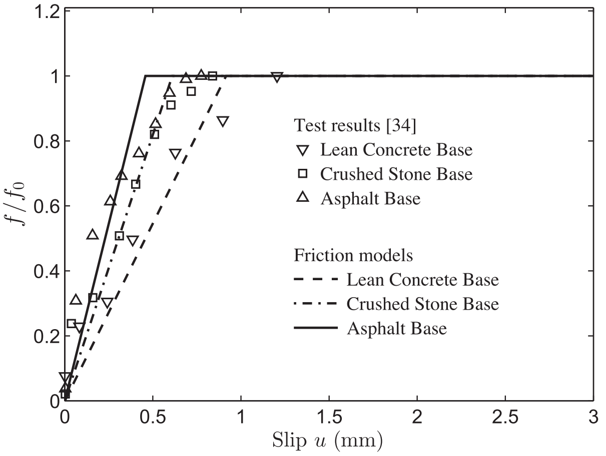


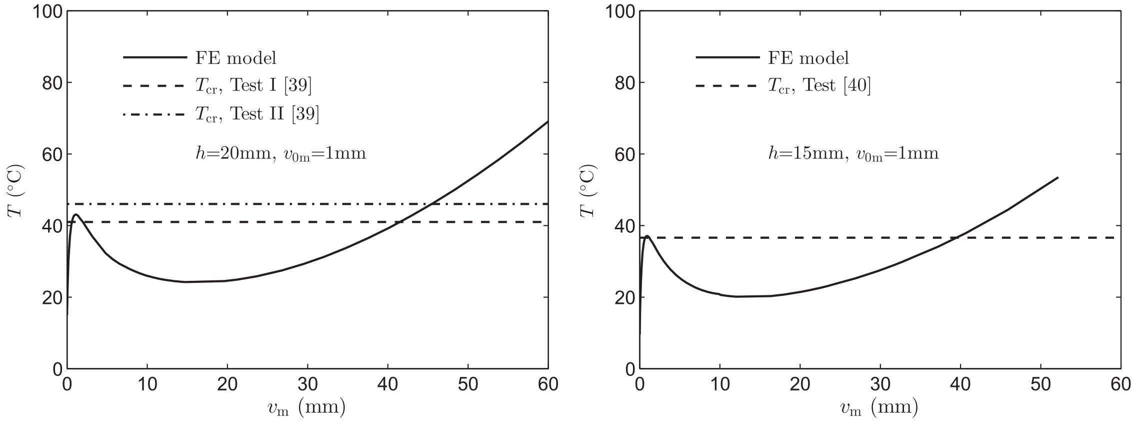
Fig. 2. Frictional behaviour between pavement and base.

Table 2
Parameters for subgrade behaviour.

USCS	Description	Typical value of Young's modulus (MPa)
CH	Clays with high plasticity	10
ML	Silts with slight plasticity	20
SP	Uniform Sand	40
GW	Well-graded Gravels	120

geometric nonlinearities introduced by finite deflections and curvature of the deformed beams were incorporated. Wadee et al. [20] found that buckling localisation may take pace in the postbuckling stage, i.e. the buckled configuration may evolve from a periodic shape to a localised shape, and this was extended by Yang and Bradford [21]. These research contributions assume that the beam is attached to the foundation in the postbuckling regime, which is appropriate for the lateral buckling of railway tracks [22] and subsea pipelines [23], whereas the buckling mode of a pavement is that of upheaval buckling, which is much more complicated for an analytical study. Refined modelling based on the finite element method may be adopted, with the stiffness of the pavement and the separation between the pavement and base taken into account.

Significant recent research on finite element analysis of railway tracks and pipelines can be found in the open literature [24–26]. Carvalho et al. [27] failed to capture the unstable path of the thermal-induced lateral buckling of railway tracks using the code ANSYS, but they proposed an approximate method to estimate the safe temperature. Karampour et al. [28] proposed a tabulated analytical solution for upheaval buckling based on a long heavy elastic beam resting on a rigid frictional foundation, and compared the response under three types of localised initial imperfection. Wang et al. [29] adopted a finite element method with dimensional analysis to investigate the upheaval buckling response and critical buckling force for pipe-in-pipe systems with full-contact imperfections. A quasi-static analysis was conducted and the unstable path was skipped by choosing a dynamic method with numerical damp-



(a) $v_m = 0.1$ m

(b) $v_m = 1.0$ m

Fig. 3. Comparison between analysis resuslts and test results of buckling temperatures.