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Thermal-induced upheaval buckling of concrete pavements incorporating the effects of temperature gradient

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ABSTRACT

Thermal upheaval buckling of continuously reinforced concrete pavements is widely reported around the world in conjunction with the evolution of global warming trends and increasing numbers of prolonged heatwaves, and which may lead to catastrophic scenarios. Such heatwaves may produce a large temperature gradient through the thickness of the pavement, and there is a need to examine the effects of a temperature gradient on pavement buckling. This paper proposes an analytical closed-form model for the thermal upheaval buckling of pavements, with a temperature gradient being embedded in the formulation. The principle of stationary total potential is employed to develop the non-linear equations of equilibrium for the postbuckling response of the pavement, and these equations are solved analytically by considering both the lift-off region and the adjoining region. It is found that the temperature gradient has no influence on a continuous lengthwise-symmetric pavement, so two pavement types are analysed in this investigation, one is a continuous pavement with a joint and the other is a continuous pavement adjoining a rigid structure. The paper demonstrates that a positive temperature gradient will lower the safe temperature of a concrete pavement with a joint, while it raises the safe temperature of a pavement adjoining a rigid structure. The buckling and postbuckling responses of pavements with different characteristics are analysed by considering the temperature gradient; the parameters being the pavement thickness, pavement base and effective weight.

1. Introduction

The buckling of continuously reinforced concrete pavements subjected to thermal loading has received widespread interest with the increasing number of prolonged heatwaves being experienced and associated with global warming [1,2]. Pavement buckling can clearly lead to loss of life and limb and it may incur significant financial losses. Several researchers have studied the bucking behaviour of pavements. Kerr and Dallis [3] established the blowup mechanism for concrete pavements based on the assumption that they are caused by thermal lift-off buckling of the pavement, in which the concept of a safe temperature was defined. Kerr and Shade [4] contributed to a better understanding of the mechanics of pavement buckling and a determination of the essential parameters by extending the bilinear approximation of the resistance between the pavement and the base to a hyperbolic tangent function. Another case of a pavement model, viz. a long continuously reinforced concrete pavement adjoining a rigid structure, was analysed by Kerr [5]. More recently, Croll [6] discussed the mechanics involved in the upheaval buckling of pavements and described the analysis for buckling in two separate models; one being a one-dimensional beam and the other a two-dimensional plate. In this and other research, however, the temperature increase was assumed to be homogeneous, while field tests show that large temperature gradients can develop, as the temperature of the top layer is usually much higher than that of the bottom layer, when the pavement is exposed to heatwaves [7,8]. This temperature gradient may play a significant role on the buckling of pavements.

The effects of a temperature gradient on structural buckling have been investigated by many researchers. Pi and Bradford [9] presented a systematic treatment of classical buckling analysis for the thermoelastic lateral-torsional buckling and for the in-plane thermoelastic flexural buckling of a fixed beam of doubly symmetric open thin-walled cross-section that is subjected to a linear temperature gradient field over its cross-section. It was found that the fixed beam may bifurcate from its primary equilibrium state to a buckled equilibrium configuration with an increase of the temperature gradient and the average temperature. Subsequently, Pi and Bradford [10] conducted a non-linear thermal buckling analysis of circular shallow pin-ended arches that are

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subjected to a linear temperature gradient field in the plane of curvature of the arch. The bending action produced by the curvature change and the axial compressive action produced by the restrained axial expansion caused by a temperature gradient was shown to potentially cause the arch to buckle suddenly in the plane of its curvature. It has also been found that temperature plays an important role in the buckling of beams at elevated temperatures [11,12] and in the buckling of functionally graded plates [13]. Therefore, it is also necessary for completeness to incorporate the effects of a temperature gradient on the upheaval buckling of continuously reinforced concrete pavements.

A concrete pavement may be regarded as a beam on an elastic foundation, and most of the previous work on this topic considered a beam attached to a foundation, for which the beam will not separate from the foundation in the postbuckling stage [14–17]. Wadee et al. [18] showed that symmetric buckling localisation can take place on a beam attached to a foundation with softening, and Yang and Bradford [19] found later that both symmetric buckling and antisymmetric buckling may give rise to a postbuckling localisation, which explains the localised lateral buckles observed in railway tracks [20,21] and pipelines [22,23]. It is generally accepted that temperature gradient does not need to be considered in the analysis of railway tracks and pipelines, as steel possesses excellent thermal conductivity [24–26]. In deference to a beam attached to a foundation, a blowup of the pavement will lead to the separation between the pavement and the base. Similar to that of railway tracks and pipelines, the non-linear equilibrium path of the pavement subjected to thermal loading can be divided into three branches: a stable branch, an unstable branch and a restabilising branch, from which two important temperatures can be obtained, these being the critical temperature and the safe temperature [27]. The critical temperature is sensitive to an imperfection, and usually the safe temperature is taken as the buckling criterion for pavements. Yang and Bradford [28] found that the stiffness of the foundation had no obvious effect on the safe temperature. Therefore, when the safe temperature of a pavement is required, the foundation can be assumed to be rigid, which is consistent with the basic assumptions adopted in Refs. [3–5,29].

The model of a pavement that does not incorporate the effects of the temperature gradient has been verified against finite element analysis [28], the purpose of this paper is to quantify the effects of a temperature gradient on the thermal-induced buckling of concrete pavements. The investigation proposes an analytical closed-form solution for thermal upheaval buckling of pavements, with the temperature gradient being embedded in the formulation. The principle of stationary total potential is invoked to develop the non-linear equations of equilibrium for the postbuckling response of the pavement, and these equations are solved analytically by considering both the lift-off region and the adjoining sliding region. Two types of pavements are analysed in this investigation, one is a continuous pavement with a joint and the other a continuous pavement adjoining a rigid structure. The buckling and postbuckling responses of the pavement with different parameters are analysed by considering the temperature gradient, and the variables involved in this investigation are the pavement thickness, pavement base and the effective weight.

2. Basic assumptions

This investigation presents a buckling analysis of two pavement types: one is a continuous pavement weakened by a joint and the other a pavement adjoining a rigid structure, as shown in Fig. 1. The length of the pavement is usually much larger than the width, and the pavement can be simplified accordingly as a beam in the longitudinal direction. Hence, the upheaval buckling of the pavement is a two dimensional problem, and the coordinate system *oxy* shown in Fig. 1 is adopted. The origin of the system is located at the joint, as shown also in Fig. 1, with the x direction being in the axial direction and y in the vertical direction. As mentioned, it has been found that the foundation stiffness has no clear effect on thermal-induced buckling of pavements [28]. Accordingly, the deformation of the foundation is not taken into account in this paper, and the foundation is assumed to be rigid, which is consistent with the work reported by Kerr and Dallis [3]. In the analysis, the pavement is divided into a lift-off region and an adjoining sliding region. Only axial displacement can occur in the adjoining sliding region, and both axial displacement and vertical displacement take place in the lift-off region. The displacements in the axial direction and in the vertical direction are denoted as u and v respectively. It should be mentioned that the length of the lift-off region will vary with the evolution of the buckling process. The length of the lift-off region is l_1, and it is assumed that the weight of the lift-off region is supported by the peel point, which has been also adopted by other researchers [4,30].

It has been found that the interaction between the pavement and the base includes a cohesive effect and a frictional effect, and the axial resistance of the pavement r can be written as

$$r = r_0 \tanh \eta u, \tag{1}$$

where η is a parameter of the constitutive model, and r_0 the maximum resistance, which is formulated as

$$r_0 = bc + bp\mu, \tag{2}$$

in which b is the width of the pavement, c a cohesive parameter, p the contact stress between the pavement and the base, and μ a frictional parameter. Eq. (2) can also be rewritten as

$$r_0 = bc - q\mu, \tag{3}$$

in which q is the weight of the pavement per unit length. It should mentioned that q is a negative value in the coordinate system *oxy*. The parameters c and μ adopted in this investigation for a lean concrete base, crushed stone base and asphalt base are listed in Table 1, which is obtained from Refs. [27,31,32].

The temperature variation is assumed to be linear along the thickness of the pavement, as shown in Fig. 2. T_1 is the temperature increase at the top surface of the pavement, and T_2 is the temperature increase at the bottom surface, so that ΔT is the temperature difference $\Delta T = T_2 - T_1$, and temperature increase at the middle plane is denoted as $T = (T_1 + T_2)/2$. In the following analysis, a temperature increase means an increase of the value T at the middle plane.

3. Pavement with a joint

The axial strain at the centroid of the cross section ϵ_m and the bending curvature κ of the pavement can be expressed as

$$\epsilon_m = u' + \frac{1}{2}v'^2 \quad \text{and} \quad \kappa = v'', \tag{4}$$

in which $()' = \mathrm{d}()/\mathrm{d}x$. The stress in the pavement can then be written as

$$\sigma = E(y)[\epsilon_m - y\kappa - \alpha T(y)], \tag{5}$$

where $E(y)$ is Young's modulus of elasticity, which is the function of y;α is the coefficient of thermal expansion; $T(y)$ the temperature increase through the thickness y, which can be written as the function of the temperature at the middle plane and the temperature difference between the top and the bottom. Eq. (5) can be rewritten accordingly as

$$\sigma = E(y)\left(\epsilon_m - y\kappa - \alpha T - y\frac{\alpha\Delta T}{h}\right). \tag{6}$$

Noting that the axes are centroidal, the axial force in the pavement is formulated form Eq. (6) as

$$N = -EA(\epsilon_m - \alpha T), \tag{7}$$

in which EA can be expressed as

$$EA = \int_A E(y)\mathrm{d}A \tag{8}$$