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Thermal-induced upheaval buckling of continuously-reinforced semi-infinite concrete pavements

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ABSTRACT

In some configuration cases for concrete pavements, such as at the intersection of two road pavements or the connection of a road pavement to a bridge abutment, the pavement can be considered to be semi-infinite with one end adjoining a rigid structure. In addition, continuously reinforced concrete pavements may weaken over time as a result of corrosion, erosion, shrinkage, fatigue cracking or the like, and in these instances the weakened pavement can also be considered as being semi-infinite with a joint. This rotational joint constrains the end of the pavement, which has an effect on the potential upheaval buckling of the pavement when subjected to heatwaves. This paper presents an analytical solution for thermal-induced upheaval buckling of such a semiinfinite continuously reinforced concrete pavement when constrained by a rigid medium with a quantifiable rotational stiffness. The method of minimum total potential energy is invoked to derive the differential equations for the post-buckling response, and the equilibrium equations with variable parameters that govern the behaviour are solved analytically by considering both the deformation of the pavement and the rotational and translational restraints. Parametric investigations are conducted on the buckling response of the pavement when constrained at one end; the parameters considered being the rotational stiffness of the joint, the thickness of the pavement, the properties of the pavement subgrade base and the effective weight of the pavement. It is found that the constraint affects the buckling temperature considerably, and the so-called safe temperature increases with the rotational stiffness of the constraint the end of the pavement.

1. Introduction

Pavement upheaval buckling is observed widely in many locations around the world due to the increasing number and extent of heatwaves being experienced in a given time period [1–4]. Such upheaval buckles are clearly problematic to transportation and safety, and the upheaval buckling of pavements is one of the enduring fundamental research issues in structural mechanics. A pavement can be simplified as a beam on a foundation, and intensive investigations on bifurcation buckling of this model were conducted by Hetenyi [5] many decades ago, which is similar to buckling analysis of pipelines and railway track [6–9]. Usually, the length of the pavement is very large, so the beam in the model should be considered sensibly as being infinite. Kerr and Shade [10] and Kerr and Dallis Jr [11], in two seminal but related contributions, established the upheaval buckling mechanism for an elastic concrete pavement based on the assumption that the upheaval buckling was caused by a lift-off buckling of a finite length of the pavement. At the intersection of two roadways, the longitudinal pavement may buckle around this region under the effects of thermal loading (typically heatwaves) if the transverse pavement is much more stiff in the horizontal plane than the longitudinal one. The same situation applies at the connection of a pavement to a bridge abutment, in which the pavement can be considered to be constrained by the rigid abutment. Based on previous work [10,11], Kerr [12] extended the theory to an analysis of a long continuously reinforced concrete pavement adjoining a rigid structure, in which the pavement is assumed to be pin-ended. However, the more realistic case of thermal-induced buckling where the pavement is constrained rotationally by the rigid structure does not appear to have been investigated. A realistic modelling of the response of the subgrade stiffness that also matches reality needs to be included in such a model. In addition to the pavement constrained by a rigid structure, pavements in engineering practice may weaken over time as a result of corrosion, erosion, shrinkage, fatigue cracking or similar effects that reduce their effective cross-section [13,14]. Recently, Wang [15] investigated the bifurcation buckling of an infinite beam on an elastic foundation weakened

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by joints that were represented by rotational springs. It should be mentioned that in deference to railway track buckling [16,17] which can be considered as a beam attached to a foundation [18,19], the initial upheaval buckling of the pavement will immediately lead to a separation between the pavement and its base. At the same time, the pavement will enter its postbuckling equilibrium configuration.

It is known that two buckling points (the so-called critical temperature and safe temperature) are observed on the non-linear equilibrium path, being limit points on this path [20]. The critical temperature is the natural buckling point, at which snap-through buckling will occur irrespective of any disturbance being experienced by the pavement. When the temperature is below the critical temperature but above the safe temperature, buckling may occur due to an external disturbance such as a vehicular traversal. It has been found that the geometric imperfection of a pavement has a significant influence on the critical temperature, while the effects of such an imperfection on the safe temperature are much less profound [21]. Because of this, the safe temperature is usually taken sensibly as the buckling temperature of the pavement. It should be mentioned that the so-called safe temperature in this investigation is the safe temperature for the pavement without imperfection, and the safe temperature of the pavement with an imperfection might be slightly lower. Although useful work has been reported by Kerr and Dallis Jr [11], constraining effects and weakening effects should be taken into account in some cases. The contribution of the adjoining region should also be incorporated in assessing the safe temperature.

This paper aims to investigate the thermal-induced buckling of a pavement constrained by a rigid structure and a pavement weakened by a joint, based on a more precise frictional model between the pavement and the base obtained from test results. The methodology in some instances follows that outlined by Kerr [12] and so the general formulation and notation used in his work is adopted here. A closed-form solution is proposed to arrive at the safe temperature by considering both the lift-off region and the adjoining flat, horizontal region. The effects of several parameters, including the rotational stiffness of the constraint, the pavement thickness and pavement base frictional response, are examined in the paper based on the analytical model proposed.

2. Basic assumptions

Usually the width of the pavement is much smaller than the length, and so the pavement is represented as a beam on a foundation [12] as shown in Fig. 1, and the beam is constrained translationally and with a rotational spring at its left hand end as shown in Fig. 1(a). The uplifted portion of the pavement is denoted as the lift-off region, the length of which being l_1, and the pavement on the right is the adjoining region, which is resisted by the pavement base friction. It is assumed that the weight of the lift-off region of the pavement is supported at the peel points, where movement is consistent with the study of Kerr and Dallis Jr [11]. This reaction force at the peel point will produce a concentrated frictional force at this location. Finite element analysis shows that the vertical stiffness of the foundation has no significant effect on thermal-induced buckling behaviour of the pavement, as the stiffness of the foundation is usually very large and the compression of the foundation due to the weight of the pavement is very small [20]. The origin of the coordinate system *oxy* is located at the centre of joint, and the axial and vertical displacements of the pavement are denoted as u and v respectively. This geometrical configuration is the same as that postulated by Kerr [12].

The axial resistance of the pavement base in the adjoining region may play an important role on thermal-induced buckling of the pavement. Usually, it is assumed that the resistance of the pavement base is caused by frictional effects only. Recently, Yang and Bradford [21] found from tests [22–24] that the resistance of the pavement base includes contributions of both cohesive and frictional effects, and the relationship between the axial displacement of the pavement and the resistance of the pavement base can be written as

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

in which r is the axial resistance, r_0 the maximum resistance, and η a parameter that defines the shape of the curve. The maximum resistance r_0 is formulated as

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

where b is the width of pavement, c the cohesive parameter, p the contact stress between pavement and base, and μ the coefficient of friction. It should be noted that $bp = -q$, where q is the weight of the pavement per unit length, recognising that q is negative in the coordinate system *oxy*. Eq. (2) can therefore be written as

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

Representative values of c and μ are listed in Table 1, which were obtained by Yang and Bradford [21] from test results reported by Jeong et al. [24].

3. Analytical formulation

The strain at the centroid of the cross-section ϵ_m and the bending curvature κ of the pavement can be expressed with sufficient accuracy as

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

respectively, in which $()' = \frac{d()}{dx}$ and v is the vertical displacement of the pavement.

A pavement with a semi-infinite length with respect to the origin is considered in the analysis. The total potential of the pavement, including the elastic bending of the pavement, the axial compression in the pavement, the deformation of the longitudinal resistance at the base of the pavement and the variation of the gravitational potential, can be written as

$$\Pi = \int_0^\infty \frac{1}{2}EI\kappa^2 dx + \int_0^\infty \frac{1}{2}EA(\varepsilon_m - \varepsilon_T)^2 dx + \frac{1}{2}K[v'(0)]^2 + \int_{l_1}^\infty \int_0^u r_0 \tanh \eta\mu \, du dx - \int_0^{u_p} q l_1 \mu \tanh \eta\mu \, du - \int_0^{l_1} q v dx, \tag{5}$$

where K is rotational stiffness of the end restraint, ϵ_T the thermal strain $\epsilon_T = \alpha T$, α the (constant) coefficient of thermal expansion, T the temperature increase in the pavement above the neutral temperature, E the Young's modulus, A the area of the cross-section of the pavement, I the second moment of area of cross-section of the pavement, and u_p the axial displacement of the pavement at the point of peeling. The neutral temperature is generally considered as that at which the pavement is unstressed axially, corresponding to the temperature at which the concrete pavement was cured.

The constraint conditions for the adjoining region are clearly

$$v(x) = 0,\ v'(x) = 0,\ v''(x) = 0 \quad l_1 < x < \infty. \tag{6}$$

By dividing the pavement into the lift-off region (the displacements being u_1 and v_1) and the adjoining region (the displacements being u_a and $v_a = 0$) and invoking the Euler-Lagrange equations of variational calculus for $\delta\Pi = 0$, the governing equilibrium equations are obtained as