MODELLING THE PERFORMANCE OF JOINTED PLAIN CONCRETE PAVEMENTS TO DYNAMIC VEHICLE LOADS

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Abstract

A whole life pavement performance model (WLPPM) is being developed for jointed plain concrete pavements (JPCPs). The aim is to predict long-term degradation of JPCPs, including cracking, faulting, pumping and surface roughness, due to applied traffic and environmental loads.

A case study of part of the model is presented in which fatigue cracking along the wheel path of a JPCP due to repeated vehicle loading is investigated using linear elastic fracture mechanics (LEFM). A finite element model of several jointed slabs was developed to obtain the stress responses of concrete pavements under the combination of vehicle loads and temperature variations. A temperature field was applied to obtain the deflection and flexural stress due to curling. A quarter vehicle model was used to calculate the dynamic tyre force variation in response to the resulting periodic surface profile. pavement response influence functions were then used to combine the 'static' response of concrete slab with the dynamic tyre forces, to determine the dynamic variation of surface stress and fatigue damage predictions at various positions along the road.

The study showed that dynamic tyre forces have a significant effect on the location and magnitude of fatigue cracking in jointed concrete slabs. Cracking rate and the location of the peaks are influenced by the combination of temperature gradient, vehicle characteristics and speed and slab properties.

Keywords: Jointed Plain Concrete Pavement, Vehicle-Pavement Interaction, Whole-Life Performance Modelling, Fatigue Cracking

1. Introduction

Long-term structural performance of jointed concrete pavements is governed by a number of factors including the structural characteristics, vehicle loading, and environmental factors such temperature and moisture variation, water ingress, frost, etc. There are many complex modes of failure including joint faulting and various types of cracking.

For many years, the design of pavements was entirely empirical (Huang 1993), but with mechanistic components gradually being implemented. In order to overcome the limitations of the traditional empirical models of pavement design and analysis, mechanistic-empirical (M-E) models (such as well-known MEPDG) have been developed (NCHRP 2004).

Most pavement design procedures follow the traditional approach that assumes the tyre force to be constant as it traverses the pavement surface. Yet studies have shown that surface roughness causes passing vehicles to generate dynamic vertical tyre forces, which will have a significant effect on pavement performance and damage (Cebon 1999; Gillespie 1993; Kulakowski 1994).

Collop and Cebon (1995) developed a 'whole-life pavement performance model' (WLPPM) to study the long-term performance of asphalt pavements due to passing dynamic vehicle loads. The model predicted the way that pavements perform throughout their service life under variable conditions of traffic and environment.

There is no existing example in the literature of a whole-life pavement performance model for jointed Portland cement concrete (PCC) pavements. Although the rigid pavement model in the MEPDG (entitled M-EPDG[R]) has a module to evaluate the long-term performance of rigid concrete pavements, it does not account for the feedback mechanisms that affect the structural response of the materials and the surface profile. Consequently key features of the pavement materials and structure do not change with time due to traffic and environmental loading. Therefore failure mechanisms associated with loss of integrity of the foundation due to slab curl and pumping are neglected as are mechanisms associated with loss of strength and stiffness of the slab due to cracking. Furthermore, the distress models incorporated in the MEPDG are fully empirical.

A new user friendly software tool called 'Vehicle-Pavement Interaction' (VPI) is under development by the Transportation Research Group at Cambridge University in collaboration with Nottingham and De Montfort universities (Roebuck et al. 2012) following a similar methodology to that developed by Collop and Cebon (1995), but with a more modular structure and user-friendly interface.

One of significant differences between VPI and MEPDG is that VPI considers the dynamic interaction between pavement and vehicles. This is particularly important for jointed PCC pavements which can have significant (periodic) surface roughness due to slab curling. VPI also considers the impact of pavement properties, vehicle characteristics, and environmental factors (e.g. temperature variation) on the long-term performance of asphalt pavements. Its modular structure provides analysts with full flexibility to use either built-in models or to incorporate their own calculation modules. The VPI software does not yet have a module of the performance of rigid concrete pavements.

Overcoming the limitations of the conventional MEPDG on modeling concrete pavements and adding new modules of concrete pavement performance to the existing VPI are two important driving forces of this research. The long-term aims are: to predict long term pavement performance due to vehicle and environmental loading; to understand the key vehicle features that influence pavement degradation – and thereby make the vehicles more 'road-friendly'; and to inform the design of roads so that vehicle loading effects are correctly taken into account.

2. Whole Life Pavement Performance Model (WLPPM)

Figure 1 shows the workflow of the WLPPM approach for evaluating the long term performance of jointed plain concrete pavements. The model consists of three core parts:

(i)   Mechanistic pavement response model;
(ii) Mechanistic distress models;
(iii) Feedback models.

In the mechanistic pavement response model, the responses (stresses, strains, and deflections) of concrete pavement to the combination of dynamic tyre forces and environment variations are calculated. Then the responses at each location of interest are used as input to mechanistic distress models (fatigue cracking, faulting, pumping, fatigue damage, etc.). The predicted incremental damage is then fed back to modify the pavement structure and material properties for the next time step.

As shown in the figure 1, temperature variation affects the jointed plain concrete pavements (JPCPs)in the two ways:
   (i) Uniform temperature changes cause thermal expansion and contraction of the slabs. The magnitude of thermal stress depends on the boundary conditions and particularly the behaviour of the joints. For pavements with poor joint design (e.g. insufficient joint clearance), premature thermally-induced cracking can occur early in the life of the pavements.
   (ii) Temperature gradients through the thickness of PCC slabs cause the slabs to curl. These periodic curling profiles strongly affect the dynamic tyre force of travelling vehicles. Thus, the shape of the curled slab must be accurately characterized so that it can be input into the vehicle model to evaluate the dynamic tyre forces. The resultant curling stress due to the temperature gradient and mechanical constraints at the joints will also affect the total stress history in JPCPs.

Apart from the temperature variation, traffic loads play a key role in pavement deterioration. The vehicle model calculates the dynamic tyre forces generated in response to the resultant road roughness, as shown in the Figure 1. The total roughness consists of the sum of the initial construction roughness, curling profile, and roughness due to structural damage (e.g. faulting, etc.).

In order to evaluate the responses of pavements to dynamic tyre forces, the 'Influence Function' approach was adopted. The method has two steps. Firstly, a unit static force (applied over a fixed contact area) is applied at each point along the travelling lane. The 'primary' response of pavement (stress, strain, displacement) at any point of interest due to the moving unit load (i.e. the influence function) is stored. Secondly, the stored influence functions are combined with the wheel load histories from the dynamic vehicle models, to determine the response history at each point in the pavement, as shown in the Figure 1.

WLPPM

- Start
- Pavement Profile
- Initial Constructed Roughness
- Temperature Gradient
- Vehicle Configurations
- Traffic Model
- Temperature Change
- Load Conditions
- Dynamic Vehicle Model
- Dynamic Tyre Force
- Jointed Rigid Concrete Pavements Model
- Combination
- Curling Profile
- Faulting Profile
- Influence Function
- Thermal Stress
- Curling Stress
- Flexural Stress
- Damage Roughness
- Total Stress History
- FeedbacK
- Mechanistic Distress Models

Figure 1 Schematic diagram of the Whole Life Pavement Performance Model (WLPPM) for jointed plain concrete pavements

3. Fatigue Cracking in Jointed Plain Concrete Pavements

In the 1960s, Paris et al. characterized crack growth due to fatigue loading (Paris and Erdogan 1963). Since then, the application of fracture mechanics to fatigue problems, particularly using the 'Paris Law' and variants, has become routine.

The procedures for analysing constant amplitude fatigue under small-scale yielding conditions are well established, although a number of uncertainties remain. Variable amplitude loading, large-scale plasticity, and short cracks introduce additional complications that are not fully understood (Anderson 2005). In all fatigue laws, material loading at the crack tip is

characterized by the stress intensity factor *K*. The classic Paris Law describes the crack growth rate for mode I cracks as follows (Paris and Erdogan 1963):

$$\frac{da}{dN} = c(\Delta K_I)^m \qquad (1)$$

where *c* and *m* are Paris constants, in the following numerical simulation, $c = 2.925e-10, m = 4$ are taken. ΔK_I is stress intensity factor amplitude, which is defined as (Anderson 2005)

$$\Delta K_I = \Delta \sigma \sqrt{\pi a}\, Y(\frac{a}{h}) \qquad (2)$$

Where $\Delta \sigma$ is the stress range, *a* is the crack length and *h* is the thickness of the slab, and *Y* is a non-dimensional function of geometry, which satisfies the following empirical formula for a plate with edge cracks (Tada et al. 2000)

$$Y(\frac{a}{h}) = 1.12 - 0.231(\frac{a}{h}) + 10.55(\frac{a}{h})^2 - 21.710(\frac{a}{h})^3 + 30.282(\frac{a}{h})^4 \qquad (3)$$

It is assumed that compressive stress does not contribute to crack growth. Hence only (positive) tensile stress is included.

A two-dimensional (2-D) finite element (FE) model was constructed in Abaqus to calculate the stress in the slab due to wheel loading, as shown in the Figure 2. A 'Python' script was developed to generate the FE mesh automatically from input data defining the number of slabs, their geometry, joint types and material properties of the slab and base course. The main features of the pavement model are:

(i)   The concrete slab is assumed to be an isotropic, elastic plate. In Abaqus a number of quadratic shell element types are available to model thin Kirchhoff plates or medium thick Mindlin plates. It was found that the various formulations gave very similar results for typical concrete slab geometries, provided the mesh was sufficiently fine. S4R shell elements were used.

(ii)   The interface between concrete slab and base layer can be modelled as bonded or partially bonded. In the bonded case, full strain compatibility is enforced between the slab and base course. In the un-bonded case, movement along the interface between the two bodies may be resisted by friction but no tensile stress can be carried by the interface. If the slab and base are un-bonded, gaps between them are a possibility (e.g. due to slab curl) and the structural analysis becomes nonlinear due to lack of contact. In these cases, it is not possible to obtain the solution for multiple loads by linear superposition of single load solutions, so the computation time increases substantially.

(iii) The subgrade layer was modelled as a 'tensionless' Winkler foundation with tangential friction at the top interface.

(iv)   The (longitudinal and transverse) joints in jointed concrete pavements mainly provide shear and bending load transfer. They were modelled in Abaqus using spring elements. A gap element was used to allow for the nodes to be in contact (gap closed) or separated (gap open).

(v)   Temperature variation can be applied directly to the pavement model to generate slab curl and thermal stresses.

(vi)   Various dynamic vehicle models can be used to calculate pavement responses.

Figure 3 shows the workflow for calculating influence functions using the 2-D Abaqus pavement model. A Matlab script file is used to control the sequence of input loads extract the results from the results file for the output points of interest and generate the set of influence functions.

The responses of pavements to dynamic tyre forces can be calculated from the influence functions and time-varying loads as follows:

$$R_j^{tyre}(t) = I_{kj} \cdot F_k^{tyre}(t) \tag{4}$$

Here $R_j^{tyre}(t)$ is the primary response (deflection, strain, stress) history at point j. $F_k^{tyre}(t)$ is the moving tyre force which is instantaneously at point k. I_{kj} is the influence function which is defined as:

$$I_{kj} = R^o(x_j) / F^o(x_k) \tag{5}$$

where $R^o(x_j)$ is the primary response (deflection, strain, stress) at point j. $F^o(x_k)$ is a static concentrated force at point k.

In principal, the pavement model can determine the responses at any point in the pavement for any vehicle axle configuration.
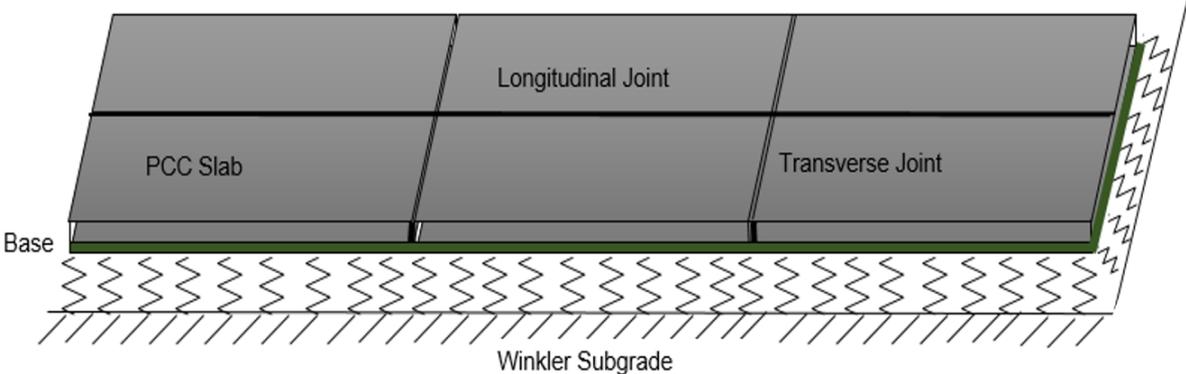
Figure 2 The illustration of jointed concrete pavements
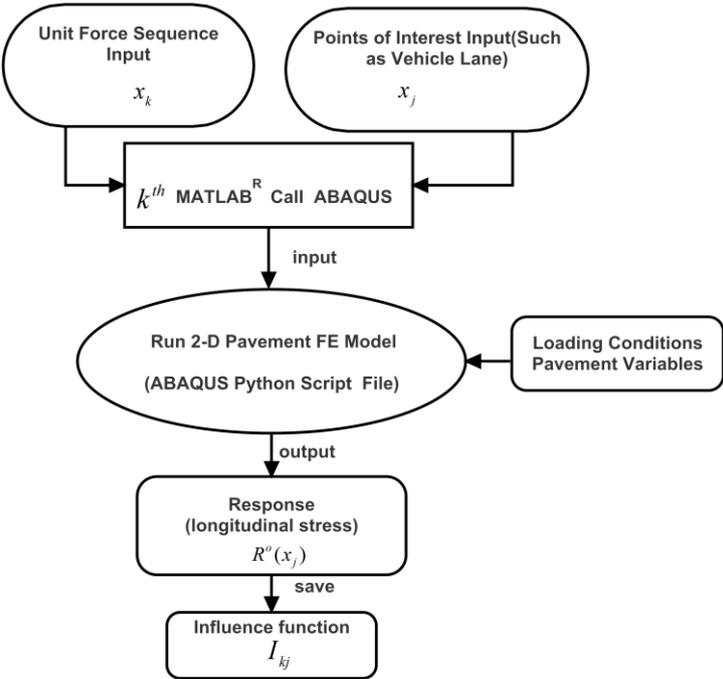
Figure 3 Calculating influence function using an Abaqus pavement model

4. Sample Calculations

For pavements with good load transfer between slabs, the maximum tensile stresses due to tyre forces are normally located on the bottom surface of the slabs under the position of the force. It is therefore reasonable to assume that cracks initiate at the bottom of the slab and propagate upwards: so-called 'bottom-up' fatigue cracking.

In order to calculate the stresses in a 'typical' slab in a jointed concrete pavement, it is necessary to model a pavement section consisting of five jointed slabs, two before and two after the central slab of interest. It can be shown that for five slabs, the curling deformation of the middle slab due to temperature gradients is the close to the correct 'periodic' solution, irrespective of the boundary conditions at the two ends of the pavement section. In the calculations discussed in this section, it was assumed that a single micro-crack existed at the bottom of the middle slab on the wheel path, as shown in Figure 4. Under cyclic stress due to vehicle loading, this micro-crack was expected to propagate upward.

It was assumed that all passing vehicles had the same dynamic characteristics and speed. The dynamic tyre forces were calculated by simulating the motion of the quarter vehicle model shown in Figure 4 in response to periodic roughness due to slab curl. That is, the road profile was assumed to be a periodic version of the deflected shape of the middle slab of the 5-slab system. The dynamic tyre forces were multiplied by the influence function, as per equation 4, to calculate the dynamic stress at the location of the crack.

Figure 5(a) shows the crack growth rate da/dN for an initial short crack with $a/h = 0.01$. This can be seen to be a non-monotonic function of vehicle speed v. The crack growth is significantly different for downward and upward curling profiles[1] and fluctuates considerably with the speed of vehicle. This is due to the effect of slab curl on the dynamic tyre forces and the resulting stress pulse at the site of the crack.

Figure 5(b) shows the crack growth rate versus slab length. For both upward and downward curling profiles, crack growth is a non-monotonic function of the slab's length. If the slab is short, crack growth is relatively slow. As slab length increases, crack growth rate first increases to a higher value and slowly decreases to a lower value before increasing again. The fluctuation is largely caused by variation of dynamic tyre forces with slab length: certain slab lengths excite resonant responses in the vehicle, depending on its speed. The general increase in crack growth rate with slab length is mainly caused by the structural properties of the system. On average, a long slab is more likely to generate a higher crack growth rate at the centre of the slab than a shorter one.

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[1] Upward curling occurs at night when the underside of the slab is hotter than the top. Downward curling occurs during the day when the top surface is hotter than the bottom.
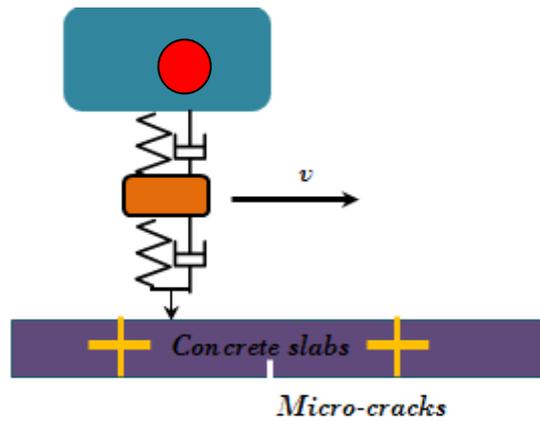
Figure 4 A quarter vehicle model traversing a concrete pavement with a single initial micro crack at the bottom of a selected slab.

| (a) | (b) |
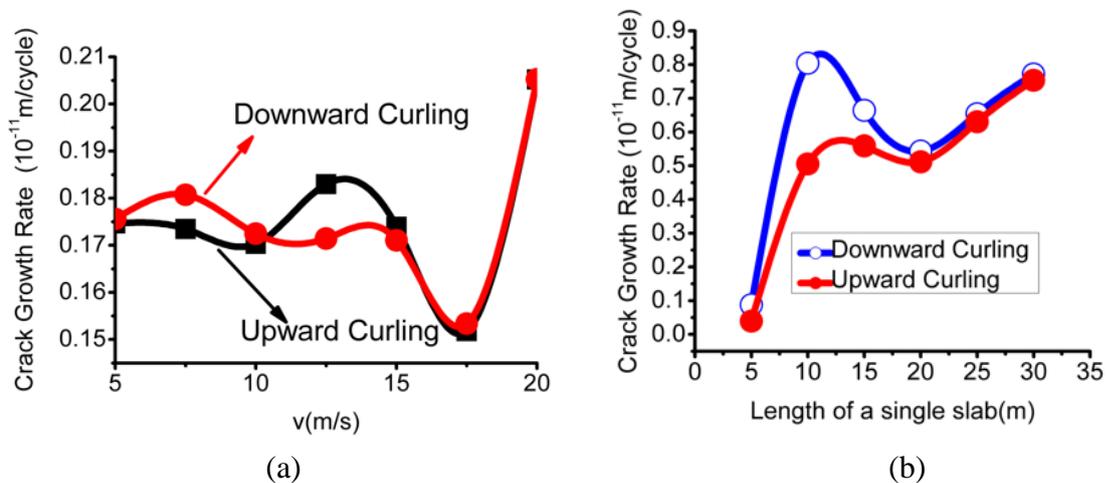
Figure 5 Crack growth rate versus (a) vehicle speed on various profiles (b) slab length

5. Case Study

In service, many micro-cracks may exist at the bottom of concrete slabs, as shown in Figure 6. Any one of these cracks might propagate during the life of the pavement. To investigate this fatigue mechanism, it was assumed that multiple parallel cracks, all with $a/h = 0.01$, initially existed at the bottom of the middle (third) slab in the same 5-slab system. The cracks were assumed to be independent during the early growth phase: interaction between adjacent cracks in the process of crack propagation was ignored.

Figure 7 shows the initial crack growth rates of nine micro cracks on the underside of the middle slab (from 10m to 15m along the pavement section) with three different temperature differences between the top and bottom surfaces of the slab. A temperature difference of 0°C corresponds to a flat surface, while a temperature difference of ΔT=10°C gives downwards curling at the edges of each slab and a temperature difference of ΔT=-10°C gives upwards curling.

Cracks at different positions along the slab have differing growth rates, due to both the changing structural 'sensitivity' and the variation of dynamic force level with distance along the slab. For the road profile without curling, the force level is constant with distance and the largest crack growth rate occurs at the middle of the slab. With downwards curling ($\Delta T=10°C$), the highest crack growth rate occurs at 13m – i.e. 2m from the downstream end of the slab. For upwards curling ($\Delta T=-10°C$), the highest crack growth rate occurs at 11.5m, i.e. 1.5m from the upstream end of the slab, and is almost twice the rate for slabs without any curling or dynamic tyre forces. Ignoring dynamic tyre forces would therefore underestimate crack growth rate by a factor of 2 and would predict the wrong location for the crack.
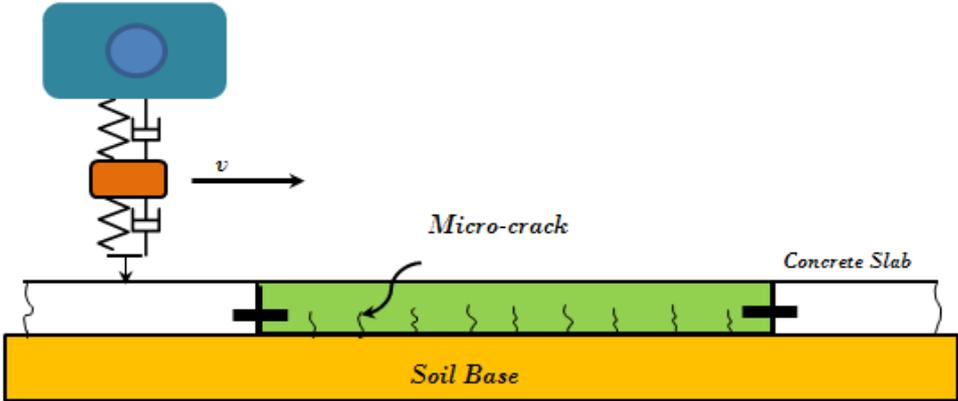
Figure 6 A pavement slab with parallel micro-cracks along the bottom surface
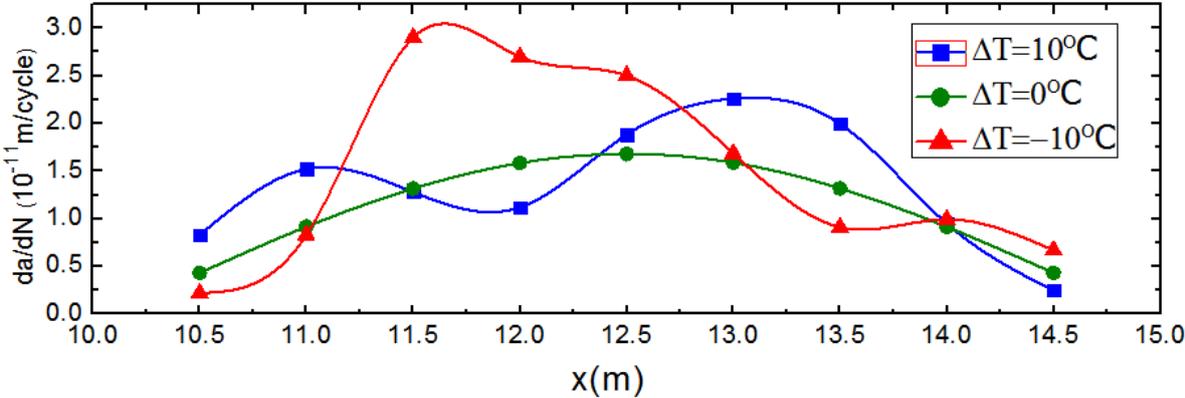
Figure 7 Growth rates of nine micro cracks on the bottom of the middle slab of a 5-slab system, for various through-thickness temperature differences.

6. Conclusions

(i)   This paper has described a whole life pavement performance model (WLPPM) which considers dynamic interaction between vehicles and jointed concrete pavements. 'Bottom-up' fatigue cracking of a single initial crack and a set of parallel cracks under vehicle loadings were studied by applying linear elastic fracture mechanics.

(ii) The results show that the initial cracking rate and the location of the peak are influenced by the combination of road profiles, vehicle speed and slab properties. Fatigue cracking rate is a non-monotonic function of vehicle speed and slab length.

(iii) When dynamic tyre forces due to slab curl are considered in the analysis, the worst-case crack growth rate is approximately double that if dynamic tyre forces are not considered.

(iv) The existing model has a number of limitations.
   a. The calculations described here considered only a 'single pass' of the vehicle. The feedback of surface and structural degradation during the service life were not considered.
   b. The quarter vehicle model with a single wheel path is a substantial simplification. Real vehicle configurations and spatial repeatability of axle loading and speed variations need to be considered.
   c. The Paris law is only valid for cyclic stress with constant amplitude. The actual vehicle loading causes a variable amplitude cyclic stress.
   d. The interaction between adjacent cracks was ignored.
   e. The FEA model of the slab and foundation assumed linear elastic material behaviour. In practice, concrete pavements and the supporting granular foundations can show strongly nonlinear material responses.

Future development of the model and case studies will consider all of these factors.

7. References

- Anderson, T. L. (2005). *Fracture mechanics: fundamentals and applications*, CRC press.
- Cebon, D. (1999). *Handbook of vehicle-road interaction*, Swets & Zeitlinger Publishers, 2000.
- Gillespie, T. D. (1993). *Effects of heavy-vehicle characteristics on pavement response and performance*, Transportation Research Board National Research.
- Huang, Y. H. (1993). *Pavement analysis and design*, Pretice-Hall, Englewood Cliffs, NJ.
- Kulakowski, B. T. (1994). *Vehicle-road interaction*, ASTM International.
- NCHRP, N. C. H. R. P. (2004). "Guide for Mechanistic-Empirical Design of New and Rehabilitated Structures. ." *NCHRP Report 01-37A*, Transportation Research Board, Washington, DC.
- Paris, P., and Erdogan, F. (1963). "A critical analysis of crack propagation laws." *Journal of Basic Engineering*, 85, 528.
- Roebuck, R., Goodrum, W., Isola, R., Cebon, D., and Collop, A. (2012). "Vehicle-pavement interaction modelling." *HVTT12*.
- Tada, H., Paris, P., and Irwin, G. (2000). *The Analysis of Cracks Handbook*, New York: ASME Press.