FRACTURE MECHANICS IN PAVEMENT DESIGN

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ABSTRACT
Pavement materials are subjected to high-cycle loading regimes. Conventional design methods employ the Palmgren-Miner damage hypothesis to predict the fatigue life of pavement materials. The material itself is usually characterized in the analysis by a measured material parameter. This approach is practical and can readily be calibrated, but does have some known shortcomings. The aim of the paper is to discuss some of the limitations of empirically based, Palmgren-Miner type, damage laws. The paper also seeks to promote the use of size independent material properties to characterize pavement materials. Some material properties used in current methods, such as the concepts of strain at break and flexural strength are known to exhibit size effects. Examples of the use of fracture mechanics providing an alternative to these conventional design parameters are given in the paper. The paper shows that although much further development is required before fracture mechanics can be relied upon to fully replace the Palmgren-Miner type damage laws, some of the concepts can already be applied to improve pavement design methods.

INTRODUCTION
In a key note address at the 26th annual Southern African Transport Conference, Ioannides (2007) highlighted the need for a paradigm shift in pavement engineering. An important part of the envisaged paradigm shift would be the replacing the Palmgren-Miner type damage laws, with fracture mechanics based models. The use of fracture mechanics to analyse crack propagation in pavement materials is slowly gaining ground. Significant theory development is still required before fracture mechanics can be relied upon to completely replace Palmgren-Miner type damage laws for fatigue in pavement design. Practical fracture mechanics based models for fatigue prediction are emerging notably for concrete pavements (e.g. Gaedicke et al 2009).

The objective of the present paper is to show how fracture mechanics principles can already be used to improve design methods. Fracture simulation allows a better understanding of fracture formation and propagation in pavement materials. Crack modelling provides a mechanistic alternative to the flexural strength parameter currently used in pavement design methods.

The paper starts with a discussion of the limitations of Palmgren-Miner linear damage hypothesis, followed by a discussion of the rationale behind the use of fracture mechanics in pavement design. To demonstrate some practical applications of fracture mechanics for pavement design a cohesive crack approach is used to simulate fracture laboratory tests on asphalt and concrete. Conclusions on the potential of fracture mechanics to improve pavement design methods are provided at the end of the paper.

The Palmgren-Miner linear cumulative damage hypothesis and its limitations
Material fatigue is defined as: the growth of damage to a material as a result of repeated loading with an amplitude lower than the ultimate stress limit of the material. Fatigue damage starts at a molecular level with a crystallographic defect, or dislocation, resulting in slip bands followed by micro cracking. Under continued loading a micro crack in the weakest position of the affected area will, at some stage, develop into a macro crack. The macro crack eventually propagates to a critical size, resulting in failure.

In pavement engineering, structures are designed to withstand a high number of loading repetitions of a specified magnitude. A fatigue life of between 10^5 and 10^8 loading cycles, is generally referred to as high-cycle fatigue. Most current pavement design damage models are based on the linear damage hypothesis for high-cycle fatigue first introduced by Palmgren but best known for the work by Miner (1945). The Palmgren-Miner linear cumulative damage hypothesis is shown as Equation 1

$$\sum \frac{n_i}{N_i} = 1 \qquad (1)$$

Where:
n_i = Number of stress cycles applied at stress level S_i,
N_i = number of cycles to failure at stress S_i

Some major limitations of Equation 1 for the use in pavement engineering can be identified:

- It is a linear cumulative function, while fatigue distress development follows a distinctly non-linear path,
- It does not take the sequence of loading into account, many small loads followed by a large load can have less of an impact on fracture propagation than the opposite sequence where a large load is followed by smaller loads, or vice-versa due to the distribution of residual stresses,
- The equation does not take the probabilistic nature of damage into account. Every load repetition only has a probability of causing additional damage. Under the Palmgren-Miner hypothesis each load repetition results in additional damage.

Despite these known limitations much of the current pavement research is aimed at further calibrating existing empirical damage models with new data. An argument can be made that this type of research will yield diminishing returns, as it will not provide a better understanding of the actual damage mechanisms at play. Fracture mechanics, as the term implies, is aimed at understanding the actual mechanism of crack formation and propagation.

The potential benefit of the use of Fracture Mechanics in pavement engineering

There are a number of reasons why it would theoretically be more correct to use fracture mechanics instead of more conventional design concepts. The two most compelling reasons are:

Firstly, although crack initiation is related to stress, which is more or less incorporated in current design approaches, the growth of a crack depends on energy dissipation. The development of a crack can only be described if both the stress at which fracture starts and the typical fracture energy G_f required to grow the crack by a unit area is known.

Secondly, many bound materials used in pavement engineering can be classified as quasibrittle and are subject to considerable size effects in fracture. This class of materials includes materials bound with cementitious binders, such as concrete and cement stabilized layers, and at low temperatures materials bound with bituminous binders. Size effect as a phenomenon is best explained using an example. Figure 1: shows two beams with the same geometry, but different sizes. According to conventional design theory and structural codes, these beams, if made from the same material, will have the same flexural strength. However, this is not the case. In general for quasibrittle materials the smaller sample can be expected to have a higher flexural strength, as indicated in the graph of Figure 1. Flexural strength, also known as modulus of rupture, depends on specimen size and is therefore not a 'true' material property. Also, due to size effect and boundary conditions beam fatigue results can not be used to accurately predict fatigue in road pavements (Roesler, 2006).

There are several sources of size effect, which can differ per material. The most important source of size effect is the fracture mechanics size effect. It is caused by differences in the amount of energy released into the fracture front. The energy release is higher for the larger beam and this leads to a relatively lower strength. Fracture mechanics allows the prediction of this size effect through the use of size independent material properties.

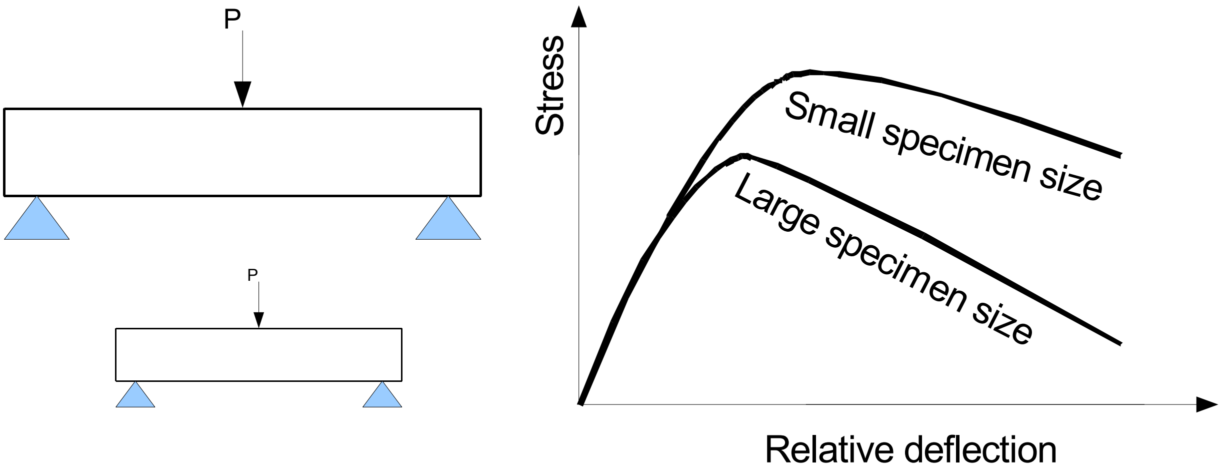

Figure 1: Size effect for beams in flexure (after Bažant and Planas 1997)

The cohesive crack approach

A range of numerical methods is available for fracture mechanics modelling of quasibrittle structures. An approach that is often used for implementation in finite element method (FEM) is the cohesive crack model. Cohesive crack modelling for concrete was first introduced by Hillerborg et al (1976). The method provides a relatively easy to understand model of the role of tensile strength and fracture energy in the propagation of a crack.

In the model, a crack is induced when the stress in the material reaches the tensile strength f_t of the material. After the crack has formed, stresses will still be transferred over the crack (e.g. through aggregate interlock), but the amount of stress transferred reduces as the crack width increases. Figure 2a shows the behaviour of model for a material that responds in a linear elastic manner before fracture. Once the stress has reached the value of f_t following a linear elastic path, a crack is formed. After crack induction the stress σ transferred across the crack is written as a softening function of the crack width w:

$$\sigma = f(w) \qquad [1]$$

Figure 2b shows a softening curve, the area under the curve is equal to the specific fracture energy G_f required to grow the crack by a unit area. The shape of the softening function differs per material. Often linear, bi-linear or exponential are used for the shape of the softening curves of concrete and asphalt. In the present paper an exponential softening function is applied. Equation 2 provides the function for exponential softening.

$$\sigma = f_t \mathrm{e}^{-aw} \qquad [2]$$

Where the value of a depends on the ratio of f_t and G_f as can be shown when integrating the softening function to obtain G_f (the area under the softening curve):

$$G_f = \int_0^\infty f_t \mathrm{e}^{-aw} \mathrm{d}w = \frac{f_t}{a} \Rightarrow a = \frac{f_t}{G_f} \qquad [3]$$

Using Equation 3 the full shape of the softening curve can be defined from f_t and G_f. The value of tensile strength f_t for a material is generally obtained from either direct or indirect tensile tests. The fracture energy G_f can be determined using slight adaptations of tests that are used on a large scale in pavement engineering practice such as three or four point bending beam tests. G_f is obtained from these bending tests by calculating the area under the load displacement curve. The area represents the total work of fracture *W.* The value of *W* is then divided by the fracture ligament area to get the value for G_f:

$$G_f = \frac{W}{bd} \qquad [4]$$

Where *b* is the width of the beam and *d* is the depth of the beam, or in the case of notched beams, the depth of the cross-section above the notch.

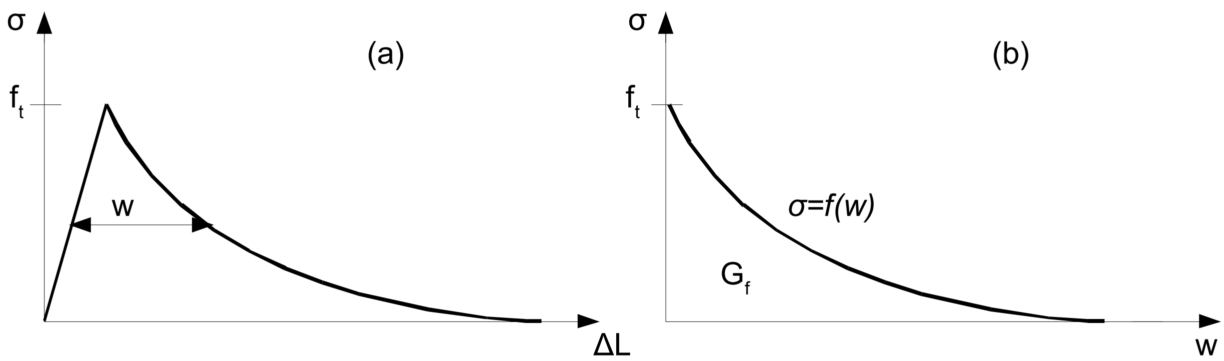

Figure 2: (a) Stress vs elongation curve. (b) Softening curve

MODELLING FRACTURE IN PAVEMENT MATERIALS

The cohesive crack approach can be incorporated in finite element method (FEM) to simulate fracture in pavement materials. In this paper an embedded discontinuity method (EDM) based on the work by Sancho et al (2007) and implemented into the open source FEM software framework OpenSees (2008) by Wu et al (2009) is used for this purpose. An advantage of the embedded discontinuity method over more conventional methods is that it allows cracks to propagate through elements, in other words, independent of nodal positions and element boundaries. The EDM was used for the numerical simulation of two examples of fracture tests on road materials from the literature. The model is applied to reproduce the results of disk shaped-compact tension (DC) tests for asphalt as reported by Wagoner et al (2005) and of three point bending (TPB) beam tests on plain concrete as reported by Roesler et al (2007). The configurations for both laboratory tests are shown in Figure 3 and the dimensions for the specimen are shown in Table 1.

Table 1: Specimen dimensions

DC dimensions	[mm]	TPB dimensions	[mm]
a	62.5	a	83
b	82.5	h	250
c	35	S	1000
D	150	L	1100
d	25	Thickness	80
e	25		
Thickness	50		

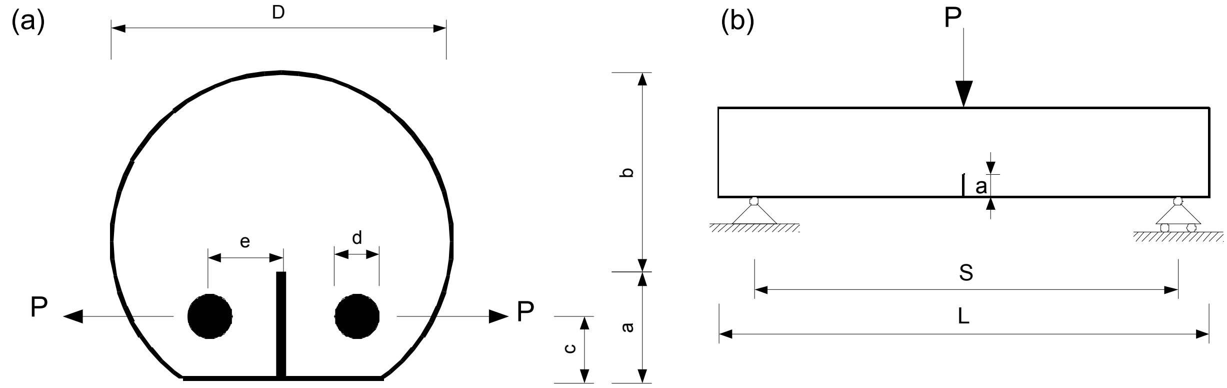

Figure 3: Test configuration for (a) compact tension test and (b) three point beam test.

The two dimensional numerical model exists mainly of triangular elastic bulk elements. These elements require the modulus of elasticity and Poisson's ratio as input. A narrow band of triangular shaped embedded discontinuity elements is provided at the notch facilitating a vertical crack path to the top of the sample. The embedded discontinuity elements behave as shown in Figure 1 and therefore require tensile strength and fracture energy to be defined in addition to the modulus of elasticity and Poisson's ratio. The material properties obtained experimentally for the asphalt by Wagoner et al (2005) and concrete samples by Roesler et al (2007) are shown in Table 2. To simulate the loading in the laboratory tests, load steps are applied in displacement control at the locations indicated with P in Figure 3. It deserves mention here that the tests on asphalt were performed at low temperatures where the material behaves in a quasibrittle fashion. At elevated temperatures more complex visco-elastic models are required to simulate the behaviour of the material in fracture.

Table 2: Material properties

Parameter	DC (asphalt)	TPB (concrete)
Modulus of elasticity E [GPa]	14.2	32.0
Poisson's ratio v	0.35	0.15
Tensile strength f_t [MPa]	3.56	4.15
Fracture energy G_f [N/mm]	0.474	0.167

Figure 4 provides an impression of the development of a crack and the distribution of horizontal stresses in the simulated compact tension test. Figure 4a shows a situation in the test before the peak load is reached. A crack has already formed in the elements at the top of the notch, but most of the elements in the ligament area are still in the linear elastic part of the material response. Figure 4b shows the horizontal stress distribution near the end of the test. The crack has propagated to about two-thirds of the height of the ligament area. The compressive zone has shifted to the very top of the specimen. The load capacity will have reduced significantly at this advanced stage of crack propagation.

The accuracy of the numerical model is assessed by comparing the load versus crack mouth opening displacement (CMOD) curves for the numerically generated and experimental data. CMOD is measured by means of a clip-on gauge at the mouth of the notch. The result of the numerical simulation of the DC test is shown in Figure 5. Wagoner et al (2005) achieved the best fit for their cohesive zone model by using a reduced fracture energy of 0.74 times the measured G_f. The results of the simulation performed for this paper are superimposed on the graph produced by Wagoner et al. A best fit was obtained applying the same calibration factor for G_f in combination with a factor of 0.85 f_t.

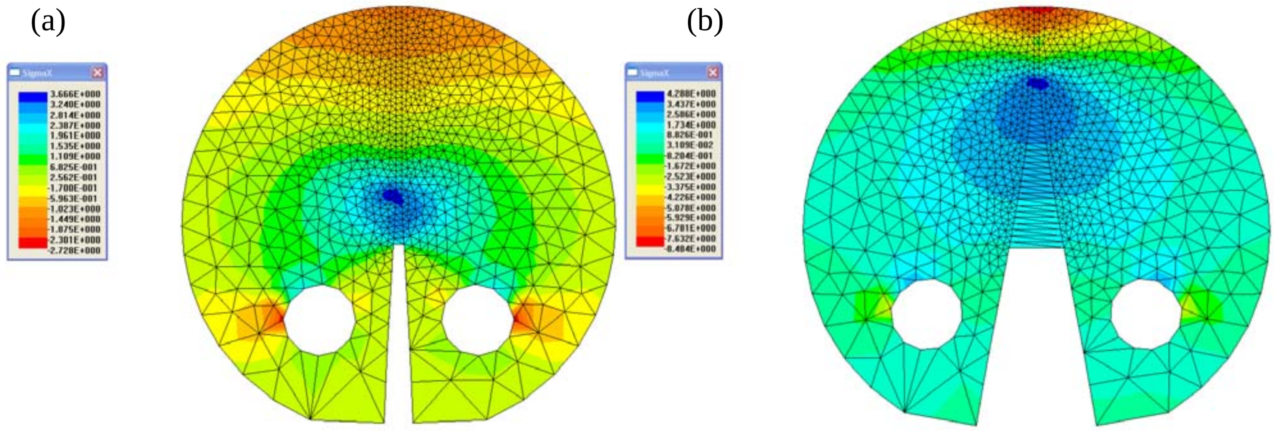

Figure 4: Horizontal stresses in disk before peak load is reached (a) and towards end of test (b)

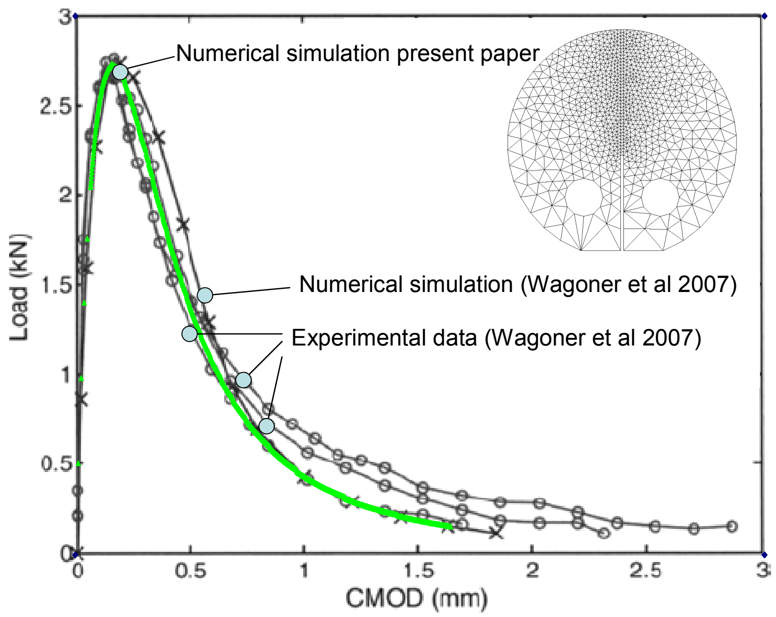

Figure 5: Comparison of load versus crack mouth opening displacement between experimental data and numerical analysis (original graph from Wagoner et al 2005).

The EDM model becomes increasingly unstable as the crack progresses past the point shown in Figure 4b. A minimum number of uncracked elements ahead of the crack front is required for the model to reach convergence. The mesh size had to be reduced from what is shown in Figure 4 and the number of iteration steps increased to allow the simulation to progress past 0.6 mm crack width.

Figure 6 shows a comparison of the experimental data for the TPB tests reported by Roesler et al (2007) and the numerical analysis performed in the present study. A good fit was obtained by applying a calibration factor of 0.8 f_t and 1.0 G_f to the values in Table 2. The material response in bending can be approximated well with the model. Note that for concrete pavement design the flexural strength or modulus of rupture would typically be used as design input. The average peak load for the tested specimen was 6.7 kN, the flexural strength would be calculated as:

$$\sigma = \frac{3Ps}{2bd^2} = \frac{3 \cdot 6700 \cdot 1000}{2 \cdot 80 \cdot 167^2} = 4.5MPa \qquad [5]$$

This value is however subject to size effect and therefore not a “true” material property. Also, if specimens without a notch were used a higher value of the flexural strength would typically be obtained. By making only small adjustments to the test procedures in use for concrete road design, the fracture mechanics parameters G_f and f_t can be determined. These allow (nearly) size independent modelling of the behaviour of pavement materials and therefore represent an improvement to the current methods. The parameters also provide a measure of the total fracture toughness of the material, whereas flexural strength only provides an indication of the peak stress.

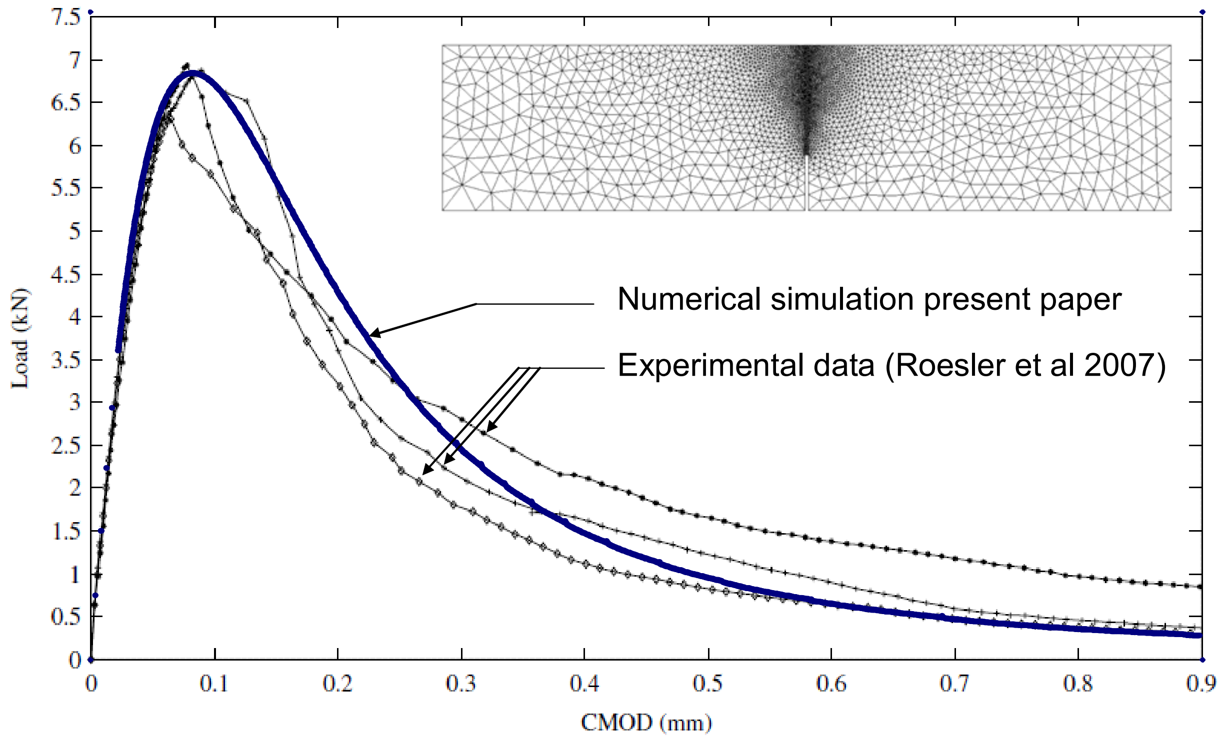

Figure 6: Comparison of experimental data with numerical analysis (original graph from Roesler et al 2007)

CONCLUSIONS

Much development work remains to be done before fracture mechanics models can fully replace the Palmgren-Miner type damage equations currently used in pavement design. However, fracture mechanics already allows the simulation of fracture propagation in pavement materials under monotonic loading.

It would be worthwhile to investigate the replacement of flexural strength, as a design input for pavement fatigue life, with fracture mechanics parameters. Not only is the concept of flexural strength limited because it is not a true material property, but fracture mechanics parameters provide a better measure of total fracture toughness.

The mechanistic simulation of high-cycle fatigue fracture in pavement materials is a topic likely to receive much attention over the coming years.

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