9 EVALUATION OF CRACK PROPAGATION IN AN OVERLAY SUBJECTED TO TRAFFIC AND THERMAL EFFECTS

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Abstract
The authors are actively involved in the development of finite element programs to study crack growth in the overlay of a structure including an anti-reflective cracking layer based on a bitumen impregnated geotextile. The program considers various positions of lorry axles and determines the total effect on the crack tip. This is combined with a temperature variation in the whole structure.
The two effects are combined in order to evaluate local damages. The F.E. program works on the following assumptions :
- the materials are elastic;
- secant moduli of the bitumen are taken into account;
- the crack has an effective width equal to the overlay maximum aggregate size;
- traffic and thermal damages can be added;
- the road structure is a semi-rigid type structure;
- the crack opening follows mode 1;
- the geotextile acts as a bitumen container and not as a reinforcement.

Keywords : reflective cracking, simulation, finite elements, model, traffic, thermal effects.

1 Introduction

The SAPLI 5 finite element programme has been developed at the M.S.M. department of Liege University for structural design. It works on mainly linear elastic mode.

As such it has been applied to simulate the crack growth in a structure constitued of (from top to bottom) (figure 1) :
- an asphalt overlay (6 cm);
- an interlayer made of a bitumen saturated geotextile (2 mm);
- a cement concrete slab (20 cm) including a vertical crack (5 mm width);
- a 15 cm thick granular subbase;
- the soil.

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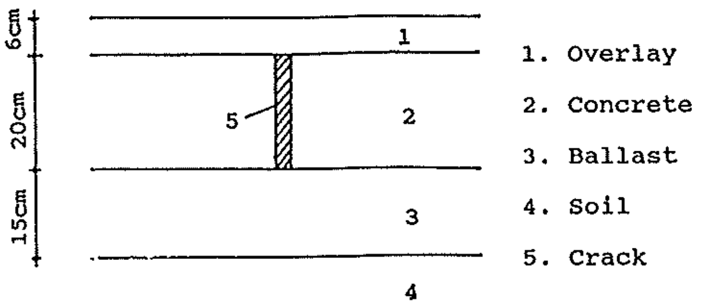

Figure 1

For this particular configuration, the objective of the work was to estimate the overlay service-life under traffic and thermal actions simultaneously.

The service life of the overlay is defined as the number of cycles of traffic and thermal loads necessary to propagate the crack across the overlay.

Fracture of a heterogeneous aggregate material such as concrete has been modelled in large finite element programs as systems of parallel cracks that are densely distributed over the finite element. This was originally proposed by Rashid (1982) and is known as the "Blunt-crack band Theory".

It has been presented by Haas (1989); Clauwaert-Francken (1989) and proved by field and laboratory observations (Rigo et al, 1989) that failures in concretes propagate with tortuosity creating a damaged zone instead of a unique crack. The cracked band width may be equal to the largest aggregates size.

The SAPLI 5 program has been used to evaluate the traffic and the thermal stresses separately and the damages induced by these stresses were evaluated and combined which permits the estimation of the overlay service life.

2 Traffic and thermal damages and their combination

2.1 Basic principle

The investigated structure has been divided into small elements by means of a 2D-finite element mesh (figure 3). The principal stresses and the resulting damages are evaluated for each element under traffic and/or thermal effects taking the stress history of each element into account. Once the damage is equal to unity for a given element, this one is removed from the mesh and the next calculation step is based on a mesh with an empty element as a simulation of the crack. This is realized step by step until the simulated crack reaches the top surface of the overlay.

2.2 Damage and crack propagation

The damage of an element is defined as the ratio between the defects surface (S_D) and the total surface (S).

$$D = \frac{S_D}{S} \tag{1}$$

If S' represents the resisting surface,

$$S' = S - S_D \tag{2}$$

The effective stress (σ') in an element is subjected to modifications in function of the evolution of the effective resisting surface

$$\sigma' = \sigma \cdot \frac{S}{S'} = \frac{\sigma}{1 - D} \tag{3}$$

If a material is subjected to damage, its elastic behavior is also affected and

$$E' = (1 - D) \cdot E \tag{4}$$

where
E = elastic modulus of the virgin material
E' = elastic modulus of the damaged material.

By assuming that the damage has a linear evolution versus the number of the applied stresses cycles,

$$D = \Sigma D_i = \Sigma \frac{n_i}{N_i} \tag{5}$$

where
D_i = the damage caused by a given stress level σ_i
N_i = the number of stress cycles at level σ_i corresponding to the failure ($D_i = 1$).
It is given by the well known Wöhler curves
n_i = the number of stress cycles at level σ_i already applied to the element.

Schmidt (1989) presented a model of the crack propagation into a bituminous surfacing. This principle is applicable to each element of the finite element mesh presented in figure 1 :

- for the initial mesh configuration (overlay without any crack) ($k = 1$). The stresses are evaluated for each element. For the one that is the most loaded it is possible to evaluate the service-life by referring to the Wöhler curve

$$n_1 = N_{1,1} = (N_{i,k})_{i=1,\ k=1} \tag{6}$$

where

n_1 = number of cycles applied to the virgin structure before removing the first element

$N_{1,1}$ = number of cycles supported by the most loaded element (N_1) before failure with the first mesh configuration.

- after failure and removal of the first most loaded element, the stresses are evaluated with the new finite element configuration. For the newly most loaded element (element 2), the service-life is evaluated by equation (7)

$$D = \frac{n_2}{N_{2,2}} + \frac{n_1}{N_{2,1}} \qquad (7)$$

where

n_1 = see equation (6)

n_2 = number of cycles applied to the second element to be removed from the mesh

$N_{2,1}$ = the maximum number of cycles to be applied for the stress on element 2 evaluated with configuration 1 of the finite element mesh

$\frac{n_1}{N_{2,1}}$ = damage supported by element 2 before element 1 failed (with configuration 1)

$N_{2,2}$ = the maximum number of cycles to be applied on element 2 for the stress evaluated with configuration 2

- for configuration 2, the number of cycles to apply before element 2 fails is

$$n_2 = N_{2,2} \cdot \left(1 - \frac{n_1}{N_{2,1}}\right) \qquad (8)$$

- for the configuration 3, the number of cycles to be applied before element 3 fails is

$$n_3 = N_{3,3} \cdot \left(1 - \frac{n_1}{N_{3,1}} - \frac{n_2}{N_{3,2}}\right) \qquad (9)$$

- the same procedure is repeated for various configurations until the crack reaches the top surface of the overlay;

- a more general version of equation (9) is given hereafter

$$n_i = N_{i.i} \cdot \left(1 - \sum_{j=1}^{j=i-1} \frac{n_j}{N_{i,j}}\right) \qquad (10)$$

or

$$n_i = N_{i.i} \cdot (1 - \Sigma D_i) \qquad (11)$$

The total service-life of the overlay is equal to

$$n_{TOT} = n_1 + n_2 + n_3 \ldots . \qquad (12)$$

It must be pointed out that at each calculation level the deterioration of the material also affects the value of the elastic modulus and equation (4) is to be applied to each finite element at each state of the crack propagation.

2.3 Combination of traffic and thermal damage

The assumption is made that the traffic and thermal damages may be calculated separately and additionned (principle of the damage superposition).
It must also be considered that thermal stresses are also cyclic loads (one cycle/day) so that the approach developed in section 2.2. herebefore is also applicable.

Considering that the traffic loads are applied with a frequency of f cycles per day, the thermal loads are applied at a frequency of 1 cycle per day :

$$\text{traffic frequency} = f \ . \ \text{thermal frequency} \qquad (13)$$

The combination of the traffic and thermal damages may thus be done as follow :

- for each element, the traffic (σ_{tr}) and thermal (σ_{th}) stresses are calculated separately;
- the Wöhler curves for the overlay permit the evaluation of
  - . N_{tr} for σ_{tr} and
  - . N_{th} for σ_{th}
- the number of cycles necessary to obtain the failure of the most loaded element of the configuration is calculated by

$$D_i = D_{i-1} + \frac{n}{N_{tr}} + \frac{n/f}{N_{th}} \qquad (14)$$

where

D_i = damage of the most loaded element for a given configuration (= 1 at failure)

D_{i-1} = damage of the same element induced by the stresses supported during the previous configurations

$\frac{n}{N_{tr}}$ = traffic damage

$\frac{n}{f.N_{th}}$ = thermal damage

Equation 13 might also be presented as follow :

$$n = (1 - D_{i-1}) \cdot \frac{N_{tr} \cdot N_{th} \cdot f}{N_{tr} + N_{th} \cdot f} \qquad (15)$$

It must be reminded that equation (4) is applicable separately for traffic and thermal loadings :

$$E_{tr,i} = E_{tr,o} \cdot (1 - D_i)$$
$$E_{th,i} = E_{th,o} \cdot (1 - D_i) \qquad (16)$$

where
$E_{tr,i}$ = elastic modulus for the traffic loads for the configuration i
$E_{tr,o}$ = elastic modulus for the virgin material for the traffic loads
$E_{th,i}$ and $E_{th,o}$ = same but for thermal loads.

3 Practical analysis of the reflection crack growth

3.1 Materials characteristics

The proposal methodology has been applied to a semi-rigid structure. The basic characteristics of the materials were the next :

- overlay

E (Mpa)	Frequency (Hz)	Temperature (°C)
5400	10	20
3100	0,1	10
2100	0,1	12,5
1330	0,1	15
390	0,1	25
210	0,1	30

The frequency of 10 Hz is supposed to be valid for the case of traffic loading while 0,1 Hz (which is not totally correct but no data are available) is supposed to be valid for thermal loading.

- the interface

Characteristics	Traffic	Thermal
G	2 Mpa	1 Mpa
E_V	1300 Mpa	1000 Mpa
E_H	4 MPa	2 Mpa
ν	0	0

where
G = the interface elastic shear modulus
E_V = the vertical (perpendicular to the interface plane) elastic modulus
E_H = the elastic modulus parallel to the interface plane
ν = POISSON's ratio.
E_V is equal to the bitumen bulck modulus in order to take into account the container effect of the geotextile. The effect also induces $\nu = 0$.

- The concrete
$E = 15.000$ Mpa
$\nu = 0,3$
$\rho = 2300$ kg/m^3
$\alpha = 12\ 10^{-6}$
The crack in this layer is supposed to be empty.

- The granular sub-grade
$E = 200$ Mpa
$\nu = 0,5$
$\rho = 2000$ kg/m^3
$\alpha = 12\ 10^{-6}$
which corresponds to a rigidity modulus K = 100 Mpa/m.

3.2 The loads

The structure is supposed to present one crack each 5 meters.
The traffic loads correspond to the local standards (13 ton/axle) and are modelled by a pressure of 6,62 bars on a 9 cm width band. This pressure and band width give in the 2D-model approximately the same principal stresses in the overlay in the cross section on top of the crack as those calculated by a 3D-model with 13 T applied with a pressure of 7 bars on a surface of 30 x 30 cm. The loads are applied at a frequency of 10 Hz. Delcuve (1990) and Hendrick (1992) have shown that the most critical position of this load correspond to the position showed on figure 2.

The overlay temperature is distributed as follow : 30°C at the top surface and 10°C at the interface. The concrete slab is subjected to a ΔT = 10°C which corresponds to a total movement of a 0,6 mm on 5 m.

It is supposed that 1000 vehicles are passing on this section per day.

3.3 Traffic loading

The load is applied as shown on figure 2.

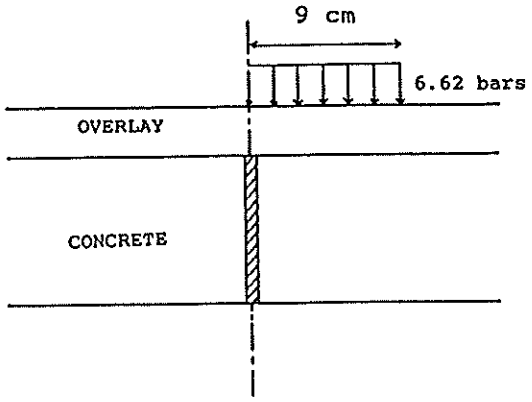

Figure 2 : traffic loads applied to the structure

Only half of the structure is studied and the results are obtained by the superposition of a symetric and a anti-symmetric loading configuration.

On the other hand, for the traffic loading the nodes at the central cross-section of the overlay have no horizontal movement (for symmetry reasons) and the relative vertical movements are blocked.

Figure 3 shows the propagation of the crack in the overlay under traffic loading only.

It must be observed that the load presence influences the crack propagation. This one is deviated transversely and appears to propagate at ± 45°.

3.4 Thermal loads

The movement of the concrete base induces very important stresses in the overlay and the crack propagation is fast and nearly vertical (figure 4).

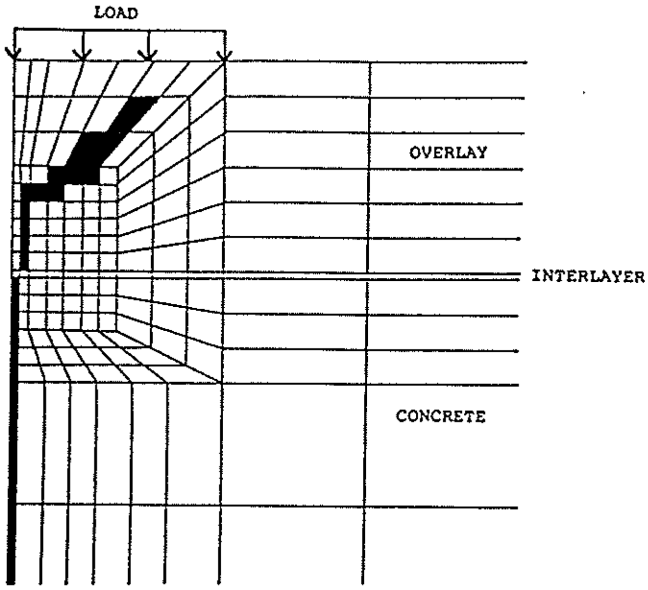

Figure 3 : Crack propagation in the overlay under repeated traffic loads

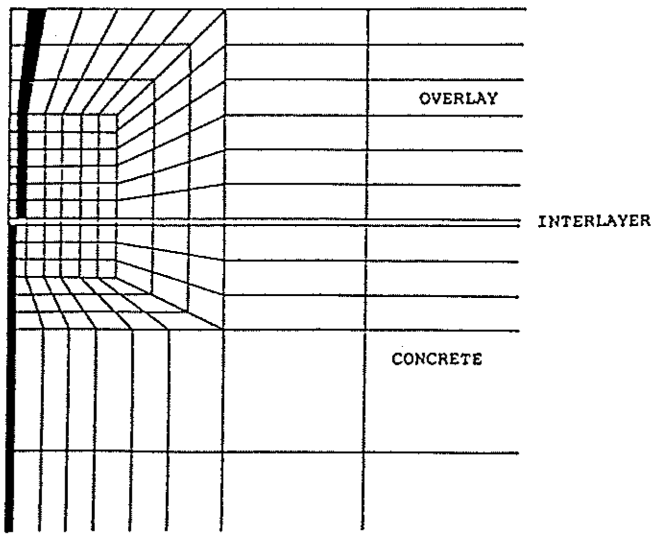

Figure 4 : Crack propagation in the overlay under thermal load

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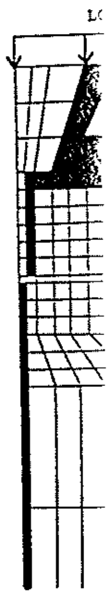

Figure 5

3.6 Crack pr
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3.5 Combined action
When traffic and thermal effects are combined the crack orientation is intermediate between the two above described situations : the crack propagates more vertically than in the case of traffic loads alone (figure 5).

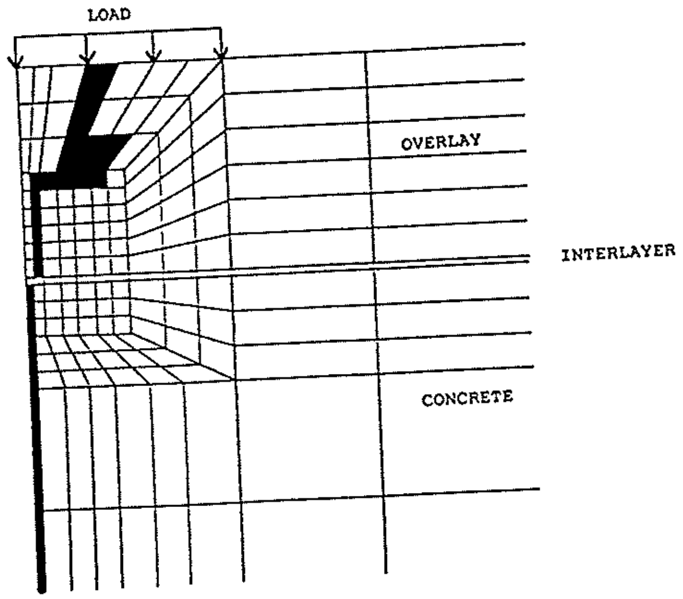


Figure 5 : Crack propagation in the overlay under combined effects (traffic and thermal)

3.6 Crack propagation
For the data presented in section 3.1. it was possible to present in figure 6 the evolution of the crack height as a function of the number of cycles. The results are expressed in days knowing that 1 thermal cycle and 1000 traffic cycles are applied per day.

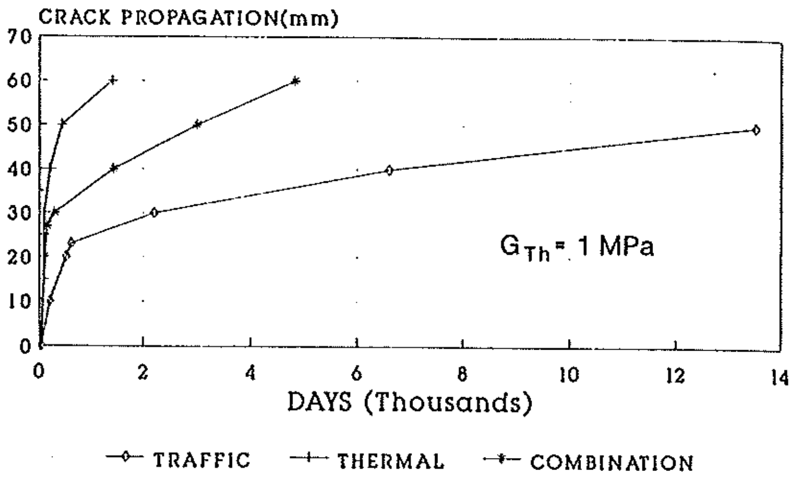


Figure 6 : Crack propagation due to traffic and/or thermal actions as a function of the days of application
(1000 vehicles/1 day, 1 thermal cycle/day)
(see parameters in section 3.1.)

4 Crack propagation as a function of the interface properties

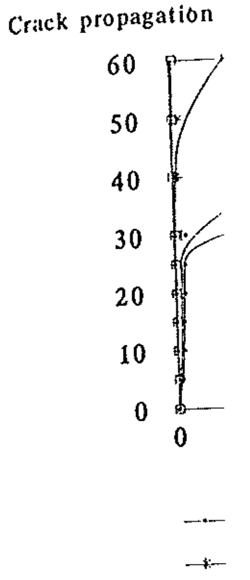
It appeared to be interesting to follow the crack propagation as a function of the G value of the interlayer.

For this purpose the elastic shear modulus was adapted and the next results were obtained.

Figure 7 gives the evolution of the overlay service-life versus the thermal shear modulus of the interlayer. For this exercise, the traffic shear modulus was kept constant and equal to 2 Mpa. All the other data reported in section 3.1. remained constant.

It can be observed that the crack propagation seems to be rapid for the early age of the structure due to an important thermal contribution and then, depending on the $G_{thermal}$ value the crack propagation is more or less slowed down.

The overlay service-life is dramatically decreased when the $G_{thermal}$ value goes up to 1 Mpa.



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5 Conclusions

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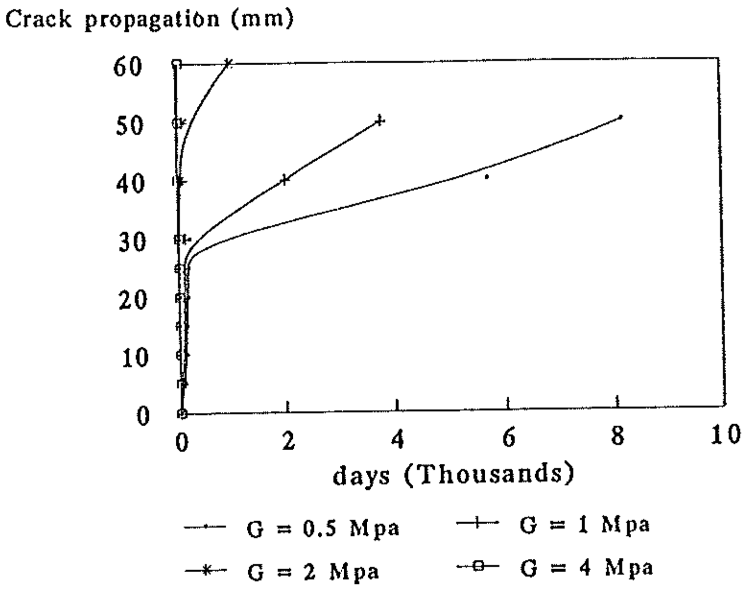

Figure 7 : The overlay crack propagation during its service-life (traffic and thermal effects) versus the thermal shear modulus of the interlayer ($G_{traffic}$ = 2 Mpa, see the data in section 3.1.)

5 Conclusions

This paper is to be considered as a contribution to the understanding of the crack propagation in overlays due to both traffic and thermal effects.

The presented method might be used in order to evaluate the crack propagation under the combined effects. It is based on a number of assumptions and data. The latter are missing dramatically in certain fields. Emphasis is to be placed on correct data collection in order to decrease the gap between calculation tools and real materials and structures behavior.

6 References

Rashid (1982). ASCE state-of-the-art report on finite element analysis of reinforced concrete. Prepared by a Task Committee chaired by A. NILSON. American Society of Civil Engineers, New York.

Haas and Ponniah (1989). Design oriented evaluation of alternatives for reflection cracking through pavement overlays. Reflective Cracking in Pavements. Assessment and Control, Liege, 1989.

Schmidt (1989). Theoretical considerations and measures for the prevention of reflection cracking in asphalt roads with cement-bound bases. Reflective Cracking in Pavements. Assessment and Control, Liege, 1989.

Clauwaert and Francken (1989). Etude et observation de la fissuration réflective au Centre de Recherches Routières Belge. Reflective Cracking in Pavements. Assessment and Control, Liege, 1989.

Rigo et al (1989). Laboratory testing and design method for reflective cracking interlayers. Reflective Cracking in Pavements. Assessment and Control, Liege, 1989.

Hendrick (1992). Etude de l'emploi des géotextiles pour la réfection des fissures des chaussées. Liege University. Faculty of Civil Engineering, Liege, 1992.

Delcuve (1990). Emploi des géotextiles dans la réparation des bétons routiers endommagés. Liege University. Faculty of Civil Engineering, 1990.

10 DESIGN OF AS
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ABSTRACT
For an asphalt/fabric repaving
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Keywords: Design, Reflective
Mechanics, Traffic, Thermal, S

1 Introduction

Asphalt overlays are applied fc
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