

# Multi-cracks modeling in reflective cracking

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**Abstract.** Reflective cracking is a major concern for engineers facing the problem of road maintenance and rehabilitation. The problem appears due to the presence of cracks in the old pavement layers that propagate into the pavement overlay layer when traffic load passes over the cracks and due to the temperature variation. The stress concentration in the overlay just above the existing cracks is responsible for the appearance and crack propagation throughout the overlay. The analysis of the reflective cracking phenomenon is usually made by numerical modeling simulating the presence of cracks in the existing pavement and the stress concentration in the crack tip is assessed to predict either the cracking propagation rate or the expected fatigue life of the overlay. Numerical modeling to study reflective cracking is made by simulating one crack in the existing pavement and the loading is usually applied considering the shear mode of crack opening. Sometimes the simulation considers the mode I of crack opening, mainly when temperature effects are predominant. Thus, this paper presents a study where multiple cracks are modeled to assess the reflective cracking phenomenon and to compare to the case of only one crack. The modeling with only one crack was made simulating both mode I and mode II of crack opening taking into account the traffic effects. The influence of multiple cracks was expressed in terms of stress and strain in the zone above existing cracks. One of the conclusions from the current study is that the presence of multiple cracks can lead to a state of stress/strain higher than those obtained with only one crack. Also the position of the crack modeled in the finite elements analysis have a significant influence in the state of stress/strain obtained. However, the consideration of only one crack is sufficient to obtain significant results in the reflective cracking modeling.

## Introduction

Cracks in the pavements tend to reflect through an overlay placed on the cracked pavement due to the traffic and temperature effects, depending on the magnitude of the stress concentrations at the tip of the crack, the resistance of the overlay material to crack propagation and the characteristics of the interface between the overlay and the existing pavement. The stress concentration at the crack tip results of the bending, shearing and tearing actions of traffic loads and tensile and bending actions caused by temperature and moisture movements as well as temperature and moisture gradients [1].

To assess the cracking in pavement overlays, many investigations have been conducted in terms of experimental and numerical modeling. The first studies started by Majidzadeh et al [2] with the application of the fracture mechanics in the analysis of pavement fatigue where the fatigue life of paving mixtures in terms of material constants, geometry, boundary conditions, and the state of stress is predicted. In that work, fatigue is defined in terms of crack initiation, influence on crack growth, and critical stress intensity at the critical failure point. The laboratory tests to support that study utilized notched and unnotched beams supported in an elastic foundation to predict the fracture parameters. The determination of the fracture parameters (i.e the stress intensity factors) were made based on experimental assumptions from fracture tests.

Later on, Van Gurp and Molenaar [3] developed a procedure to predict the reflective cracking in asphalt overlays using linear elastic finite element models, by analyzing the crack propagation form the old cracked asphalt layers through the new overlay. The models used only considered the traffic influence simulating mode I and II of crack opening by applying the load above the crack and adjacent to the crack, respectively, as represented in Figure 1.

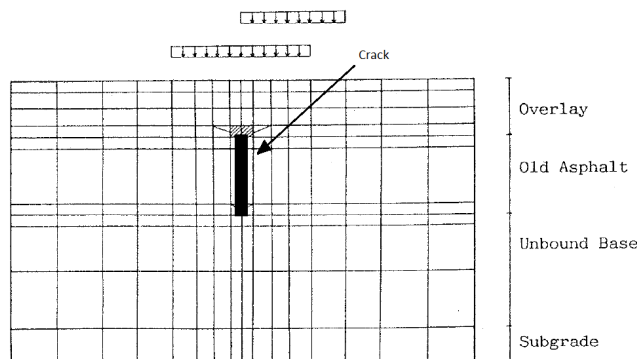


Figure 1. Single crack modeling in mode I and II of crack opening [3].

Since then, the numerical modeling has been used in the assessment of reflective cracking by different methods. Paulino et al [4] applied a cohesive zone fracture model to simulate crack initiation and propagation in asphalt concrete using intrinsic constitutive laws to connect traditional finite elements to simulate localized damage and softening behavior. Nesnas and Nunn [5] used a finite element model with multi-cracks, as indicated in Figure 2, to investigate the top-down cracking in cement treated base pavements.

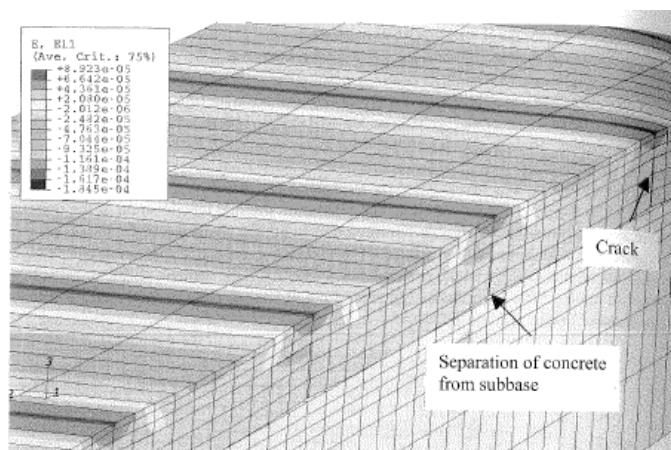


Figure 2. Multi-cracks simulation for top-down cracking [5].

More recently, Wu and Harvey [6] developed a finite element model to evaluate the performance of several asphalt mixes that contain binders with recycled rubber. The mechanistic model was based on non-local continuum damage mechanics and the finite element method and the damage evolution law parameters were identified using laboratory fatigue test data. The finite element model (Figure 3) was the first model used in the reflective cracking analysis that was created with multiple cracks, simulating the alligator cracking in the existing pavements before the placement of a pavement overlay.

However, these studies did not investigate the influence of the existence of multiple cracks or the influence of the spacing between cracks in the evaluation of the reflective cracking. This subject takes a significant importance because cracked pavements, mainly the flexible pavements, usually present multiple cracks (alligator cracks) before the pavement overlaying.

Thus, this paper aims to study the influence of the existence of multiple cracks in finite element models on reflective cracking. This influence is assessed by the state

of stress and strain in the pavement overlay, just above the existing cracks in the old pavement.

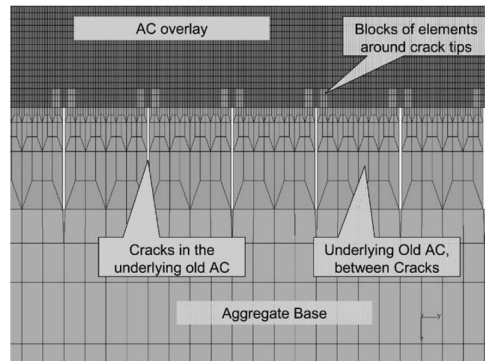


Figure 3. Multi-cracks modeling to simulate HVS effect [6].

This effort consisted of developing a 2D finite element model which was created, using the plain strain mode, in which 10 cracks were modeled in the cracked layer and spaced 10 cm from each other. The model has the ability to easily change the crack spacing, the elimination of some cracks to create any configuration of cracking with any cracking spacing, from a pavement with only one crack to a pavement up to 10 cracks.

The application of this model resulted in creating different cracking configurations to study the influence of crack spacing on the reflective cracking phenomenon. The study investigated three different overlay configurations: 10, 20 and 30 cm overlay thicknesses over an existing cracked pavement.

### Finite elements model

A 2D finite elements model was created for a pavement configuration consisting of an overlay layer, an existing asphalt cracked layer, a granular base layer and a subgrade layer, as schematically represented in Figure 4. The model considers the existence of full friction as interface between old and new pavement layers. The existing asphalt layer was modeled with 10 cracks, numbered from 1 to 10, starting from the left side of the model. The distance between cracks was set to 10 cm and the crack width was set to 3 mm. The model has the ability to easily allow the elimination of some cracks to create any configuration of cracking with any cracking spacing, from a pavement with only one crack to a pavement up to 10 cracks.

The mesh of the model was designed by using quadrilateral, two-dimensional structural-solid elements, with eight nodes, with two degrees of freedom at each node. The mesh was designed to apply a load with a dual wheel configuration representing a standard axle wheel of 80 kN (Figure 5), applied on the pavement surface in a representative area of the tire-pavement contact. The finite element model used in the numerical analysis was developed in a general finite elements code, ANSYS(R) Academic Teaching Introductory, V12.1.

The finite elements model was configured to create 25 different pavements configurations, varying the cracking configuration. The first 10 models present only one crack, from crack #1 to crack #10, representing all possibilities of isolated cracks. The following pavements represent the configurations of multi-cracks varying the cracking space from 10 cm up to 50 cm, as indicated in Figure 6.

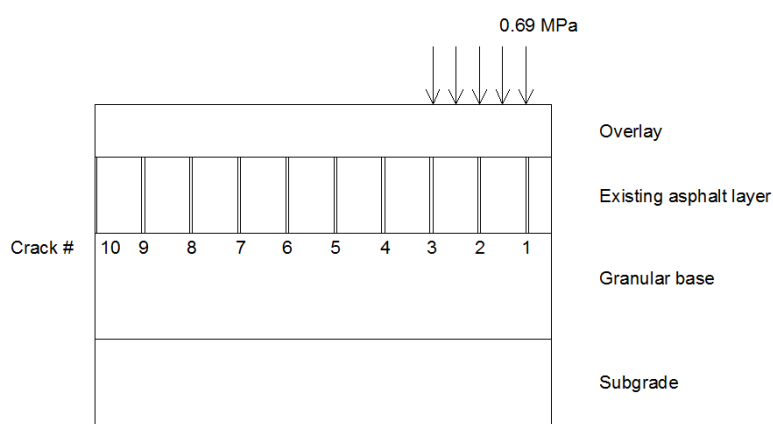


Figure 4. Schematic representation of the finite elements model.

These models were applied to three different pavement structures, varying the overlay thickness and keeping the same thickness for the layers of the existing asphalt layer and for the granular base. The thickness and stiffness of the layers for the three structures are shown in Table I. The materials were modeled assuming a linear elastic behavior.

The finite elements model was designed as a plain strain problem, using plane structural solid elements, defined by eight nodes and having two degrees of freedom at each node.

The state of stress and strain in this type of problems is governed by a stress concentration at the crack tip and needs to use the fracture mechanics for a correct assessment. To avoid the use of the fracture mechanics, the state of stress and

strain in the crack tip was calculated just above the modeled cracks, 0.3 and 0.25 mm from the crack edge, as indicated in Figure 7. For each case, the horizontal, vertical, shear and Von Mises strain was calculated.

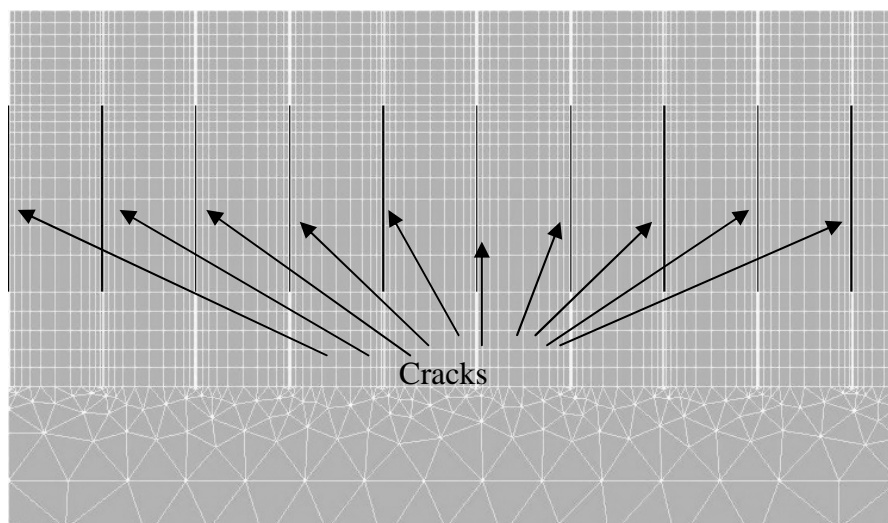


Figure 5. Finite elements model.

Layers		Structure 1	Structure 2	Structure 3
Overlay	thickness	0.10 m	0.20 m	0.30 m
	stiffness	5000 MPa	5000 MPa	5000 MPa
Existing asphalt layer	thickness	0.20 m		
	stiffness	2000 MPa		
Granular base	thickness	0.20 m		
	stiffness	160 MPa		
Subgrade	stiffness	80 MPa		

Table 1 – Thickness and stiffness of pavement layers.

## Modeling results

One of the objectives of this work was to evaluate the difference between modeling of multiples cracks as compared to a single crack. This can be observed by the representation of the Von Mises strain presented in Figure 8 and 9, respectively for a pavement with only one crack modeled (crack #3) and the pavement with 10 cm

spaced cracks (case 11). The analysis of these figures show the difference between the state of strain in the overlay associated with the presence of either a single or multiple cracks. The difference is also visible in the state of strain above the existing cracks which is responsible for the reflective cracking.

Case	Crack	Load									
		10	9	8	7	6	5	4	3	2	1
1	Single crack										1
2										2	
3									3		
4								4			
5							5				
6						6					
7					7						
8				8							
9			9								
10			10								
11	10 cm	10	9	8	7	6	5	4	3	2	1
12	20 cm	10	9	8	7	6	5	4	3	2	1
13	30 cm cracks	10		8		6		4		2	
14		10		7				4			1
15				8		5			2		
16			9			6			3		
17			9			5					1
18	40 cm cracks	10			6				2		
19					7				3		
20				8				4			
21						6				2	1
22	50 cm cracks				7					2	
23				8					3		
24			9					4			
25			10				5				

Figure 6. Representation of cracking configuration.

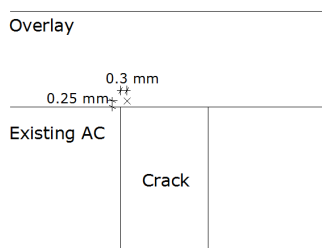


Figure 7. Location for stress and strain calculation.

The first analysis of this study of carried out for the cases of single cracks, i.e. the cases 1 to 10 where for each model only one crack was modeled in each pavement. For these cases, the strain level in the pavement with 10 cm thickness overlay is indicated in Figure 10, where Ex represents the horizontal strain, Ey represents the vertical strain, Exy represents the shear strain and the Evm represents the Von Mises shear strain.

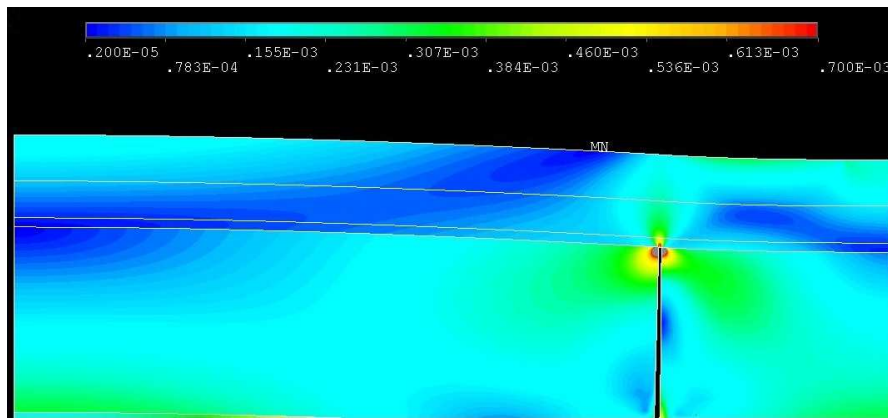


Figure 8. Von Mises strain in a pavement with a single crack (#3).

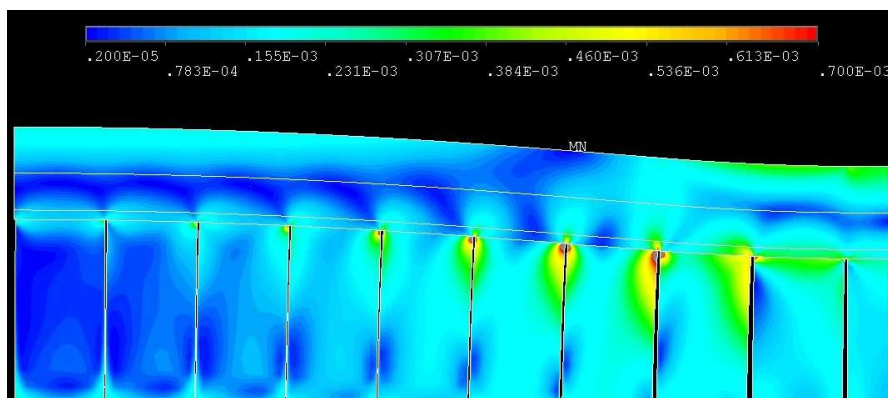


Figure 9. Von Mises strain in a pavement with multiple cracks.

The analysis of single crack modeling indicates that the vertical strain is almost constant when cracks below the load (1, 2 and 3) are modeled. Also, for the other cracks, the vertical strain is constant. In terms of horizontal, shear and Von Mises strain, they increase as the cracks moves away from the load but after crack 4 the strain level reduces significantly, except for the horizontal strain.

This analysis shows that when only one crack is modeled, that should be the crack 4, which is 10 cm away from the load. Usually, the modeling of a single crack simulating the mode II of crack opening is simulated by crack 3, which is around 20% less than the strain level above crack 4.

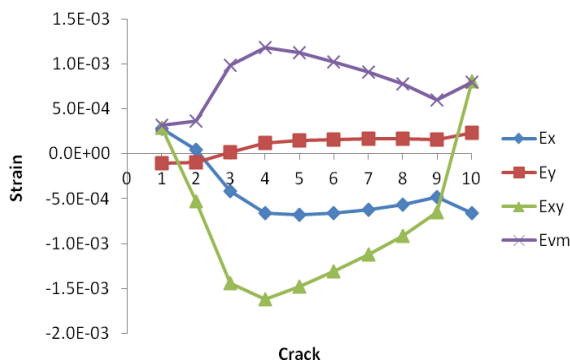


Figure 10. Strain in the overlay for models with only one crack.

For the other pavements, with 20 and 30 cm overlay thickness, the conclusion is identical, ie, the maximum state of strain appears not for the crack adjacent to the load but away from the load, as it can be observed in Figure 11 where the Von Mises strain is represented as function of the overlay thickness and crack number. As the overlay thickness increases, the Von Mises strain (Figure 11) decreases and the maximum strain appears for crack 6, ie, 30 cm away from the load.

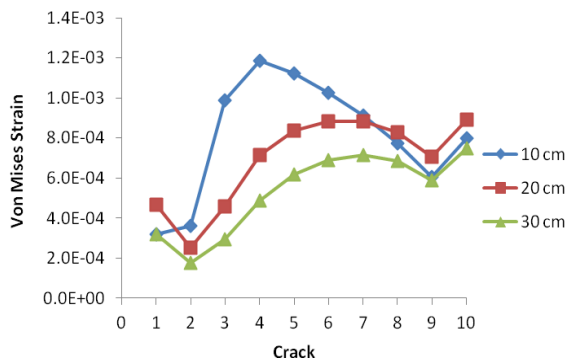


Figure 11. Influence of overlay thickness of Von Mises strain for single crack.

The modeling of multiple cracks with a spacing of 10 cm produces the results presented in Figure 12, for the overlay with 10 cm thickness, which are similar to the ones obtained for single cracks modeling. However, the comparison between Figure 10 (single cracks) and Figure 12 (10 cm cracks) indicates that the presence of 10 cm multiple cracks reduces the strain in the overlay compared to the single cracks modeling.

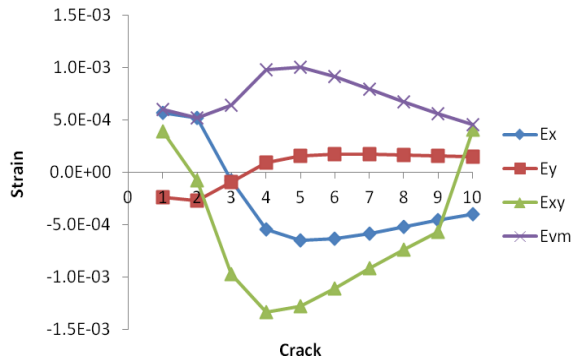


Figure 12. Strain in the overlay for 10 cm crack spacing.

For the other pavements (20 and 30 cm overlay thickness) the behavior of the Von Mises strain is identical to the observed for single cracks modeling where maximum strain appears for crack number 6 but the strain level is lesser than the one observed for single cracks. Identical results were obtained for the other strain components as well as for stress components. The analysis of 10 cm spaced cracks shows that, for this crack spacing, the consideration of multiple cracks is unfavorable.

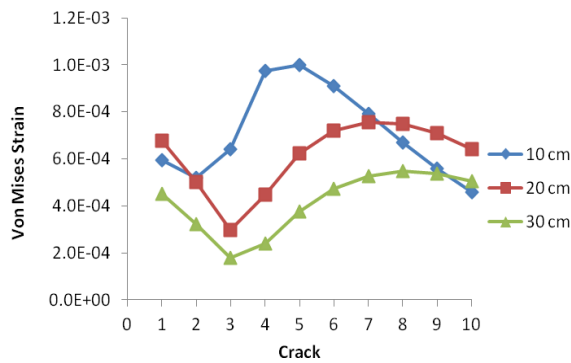


Figure 13. Influence of overlay thickness of Von Mises strain for 10 cm crack spacing.

Identical conclusion to those obtained for 10 cm spaced cracks can be obtained for 20 and 30 cm spaced cracks, as it can be observed in Figures 14 and 15. For these cases, the Von Mises strain presents the highest value for crack #5. However, the maximum Von Mises strain for 20 and 30 cm spaced cracks is identical to the one

observed for 10 cm spaced cracks, which is less than the one observed for single cracks (#4 and #5).

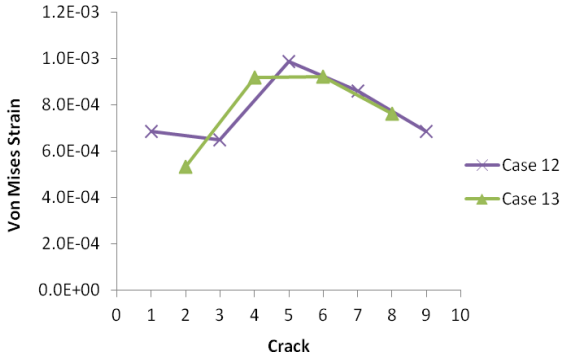


Figure 14. Von Mises strain in the overlay for 20 cm crack spacing.

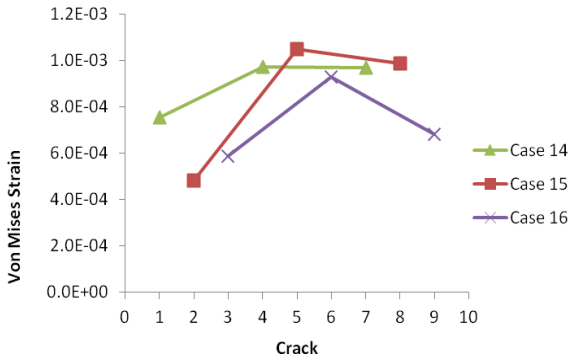


Figure 15. Von Mises strain in the overlay for 30 cm crack spacing.

Different conclusions can be obtained from the results for 40 and 50 cm spaced cracks where a Von Mises strain level greater or identical to the one obtained for single cracks (mainly for crack #4) was achieved. This appears mainly when a 50 cm crack spacing exists and there is a crack below the load and the other crack is away from the load. If the first crack is not below the load, then the strain level in that crack and in the other cracks is reduced compared to the maximum observed for a single crack #4. However, the maximum value observed for these cases is almost identical to the one observed for a single crack #4 and thus it is

enough to consider the existence of only one crack, not adjacent to the load but some centimeters away from the load, depending of the overlay thickness.

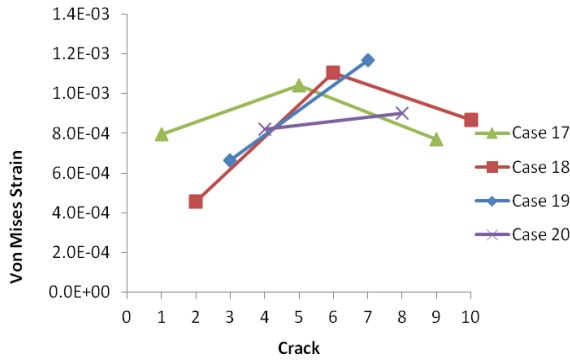


Figure 16. Von Mises strain in the overlay for 40 cm crack spacing.

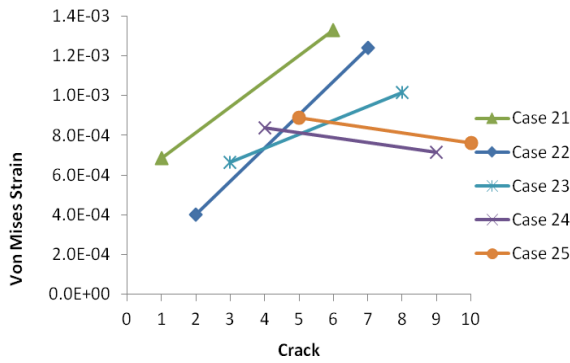


Figure 17. Von Mises strain in the overlay for 50 cm crack spacing.

### Conclusions

This paper presented a study about the influence of multiple cracks in finite element models on the reflective cracking. This influence was assessed by evaluating the Von Mises strain in the pavement overlay, just above the existing cracks in the old pavement. In the 2D finite elements models, single and multiple cracks were simulated considering a distance between cracks ranging from 10 cm to 50 cm. The following conclusions can be made from the analysis of the results:

- There are significant differences in the state of stress in the pavement overlays due to the presence of multiple cracks compared to the modeling of single cracks;
- The modeling of a single crack must be made by a crack considerable away from the load. That distance depends on the overlay thickness and for the cases studied it should be greater than 10 cm;
- The multiple cracks modeling do not increase the strain level in the overlay. However, the larger the distance between cracks, the higher and more significant the strain level can be when compared to the one obtained for a single crack.

## References

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