3-Dimensional Finite Element Analysis of Cracking

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ABSTRACT: Pavement structural analysis aims at computing the pavement response under traffic and environmental loading. Excessive stresses induced by these two loading parameters lead to various types of distresses. One of the most important distresses is cracking. This paper focuses on traffic load induced cracking that either initiates at the bottom of bituminous pavement layers propagating upwards (bottom-up) or starts at the surface growing downwards (top-down). There is a need to investigate these types of cracking by establishing analytical models capable of simulating failure mechanisms, with the view to acquire a better understanding of the pavement behaviour so that the selection and design of maintenance treatments may be optimised. To this end, this paper presents three-dimensional models that were used for a detailed behavioural modelling of a pavement and for analysing both the distribution of stresses at the vicinity of single cracks and their effect on the overall pavement strength. The models were developed using LUSAS©, a general-purpose finite element computer program, and calibrated using Falling Weight Deflectometer (FWD) field data. A good convergence was achieved between the FWD measured deflections and those calculated by the models. Further analyses showed that the presence of cracking does not affect significantly the computed deflections but primarily the stress regime within the bituminous layer. In addition, the analyses demonstrated that top-down cracking may have a significant effect on the distribution of stresses within the bituminous layers. It should therefore be analysed as a structural defect, like bottom-up cracking.

KEY WORDS: Cracking, bituminous pavement, surface cracks, bottom-up cracks, finite elements.

1 INTRODUCTION

Cracking is widely acknowledged as a major distress of road pavements caused by traffic and environmental loading, construction imperfections and poor material properties. This paper focuses on traffic load induced cracking which is associated with the fatigue properties of the bituminous layers, although traffic loading may also cause slippage cracking in wearing courses that are not bonded satisfactorily with the underlying layer. Fatigue cracking may start at the bottom of the bituminous layers and grow upwards towards the surface of the pavement, often called bottom-up cracking, or initiate at the surface of the bituminous layer and grow downwards, often known as top-down cracking.

Bottom-up cracks are known to affect the load spreading ability of road pavements. These cracks also allow ingress of water into the pavement, eventually causing weakness to the sub-base and subgrade layers and leading to further deterioration. During winter months, water entering the cracks might freeze causing formation of ice lenses that may result into upward warping of the crack edge. As a consequence of reduction of the bearing capacity of the road pavement, the cracking usually increases in extent and severity, and may ultimately result into disintegration of the pavement. Conversely, surface cracks severely affect the durability and functional performance of the surfacing of the bituminous pavements. As surface cracks become severe, spalling will occur, which could consequently lead to formation of potholes that significantly influence riding comfort and safety (Paterson et al, 1986). Bottom-up cracking is said not to be a major problem on roads in industrialised countries such as those found in the United Kingdom. This is because the road pavements are well designed to achieve a long life by limiting tensile stresses at the bottom of the bituminous layer. However, criteria for surface cracking are currently not included in design procedures; this is because the mechanisms by which surface cracks are initiated and propagated are still not well understood (Nunn et al., 1998).

Given the consequences of cracking on the structural and functional performance of the pavement, it was felt necessary to develop three dimensional (3D) finite element models with the view to simulate the pavement behaviour in the 3D space and to facilitate an understanding of the behaviour of cracking in bituminous pavements. To this end this paper presents a simplified finite element (FE) analytical method for the investigation of the effects of top-down and bottom-up cracking on the stress regime developed in bituminous layers. It gives the details of the modelling procedure followed together with its calibration to in-situ conditions. Thereafter it presents and discusses the distribution of stresses in three model variants that include a single top-down and bottom-up crack loaded both symmetrically and asymmetrically.

2 THE USAGE OF FINITE ELEMENTS

A number of models have been developed or used to date to investigate the effects of cracking or the cracking mechanism itself. Snaith et al. (1980) suggested that the effects of cracking on the overall strength of pavement may be simulated by assigning a lower modulus to the bituminous layer and subsequently analyse the response of the pavement using an FE model. Similar approaches were followed by other researchers (amongst others Freeme et al., 1987) but more recently detailed investigations have been carried out to acquire a better understanding of the stress distributions in bituminous surfacings. For example, Jacobs et.al. (1992) suggested that the stress distribution that cause surface cracking has three components: vertical stress, longitudinal shear stress in the direction of the moving wheel and transverse shear stress perpendicular to this direction. The stress distribution seems to be three-dimensional resulting in higher tensile and transverse shear stresses. Such a distribution would ideally require a 3D modelling approach (Franken et. al., 1997) but usually simpler two-dimensional (2D) or axisymmetric models are widely used. For example Myers et al., (2001) investigated the crack initiation and propagation mechanisms using the FE package ABAQUS. Dauzats et al. (1987) carried out an analysis of cracks using the 2D FE model ELIP that used principles of fracture mechanics. In addition, highly sophisticated 3D models have been used for a detailed investigation of the stress distribution under pneumatic tyres (de Beer et al., 1996) and also for crack analysis (Franken et al., 1997). This paper however investigates the usage of 3D models as part of a back analysis procedure. It reduces the complexity of modelling cracks to the simulation of a single crack with the view to acquire an insight into the manner in which cracks affect the stress regime in bituminous layers.

3 MODEL DETAILS

To facilitate the development of the FE models, a suitable set of field data was selected. These consisted of Falling Weight Deflectometer (FWD) measurements from a flexible pavement in the UK, its surface condition and the thickness of the pavement layers (Evdorides, 1994). The data used are given in Tables 1 and 2. From these data and using LUSAS$^{©}$, a general purpose FE computer programme, three variants of a 3D model were developed:

(a) an uncracked pavement model
(b) a model with a single crack at the top of the bituminous surfacing (top-down crack model) and
(c) a model with a single crack modelled at the bottom of the bituminous surfacing (bottom-up crack model).

The pavement model was developed with an overall grid dimension of 6m both in length and width in the horizontal plane. The pavement structure consisted of a bituminous surface layer of thickness 90 mm, a bituminous road base of 208 mm and a granular sub-base layer of 330 mm. The sub-grade was modelled with a thickness of 3 m. The bottom boundary of the models was fully fixed against movement. The vertical boundaries of the models were fixed against horizontal movement. A loading of 700 kPa was modelled on a circular area of radius 150 mm to simulate a loading exerted by the FWD. 3D continuum isoparametric hexahedral elements capable of modelling 3D stress fields were assigned to the models. Details of the model geometry and mesh may be seen in Figures 1 and 2.

45mm deep and 1mm wide bottom-up and top-down cracks were fitted into the uncracked pavement model by creating a material discontinuity in the FE mesh. The 45 mm length of crack was necessary to ensure that the tips of both the top-down and bottom-up cracks are located at the same horizontal plane, at the mid-point of the bituminous surfacing that had a thickness of 90mm. Both top-down and bottom-up cracks were modelled along the 6m length of the model, as shown in Figures 1 and 2.

Table 1: Pavement structural data

Surface condition	Thickness of layers (mm)		
	Bituminous surfacing	Bituminous road base	Granular sub-base
Cracked	90	208	330

Source: (Evdorides, 1994)

Table 2: Measured deflections (microns) and normalized to a reference stress of 700 KPa

Applied stress (kPa)	Radial distances (mm)						
	0	300	600	900	1200	1500	2100
	Deflections (microns)						
748	274	216	166	124	94	70	41
700	256	202	155	116	89	66	38

Source: (Evdorides, 1994)

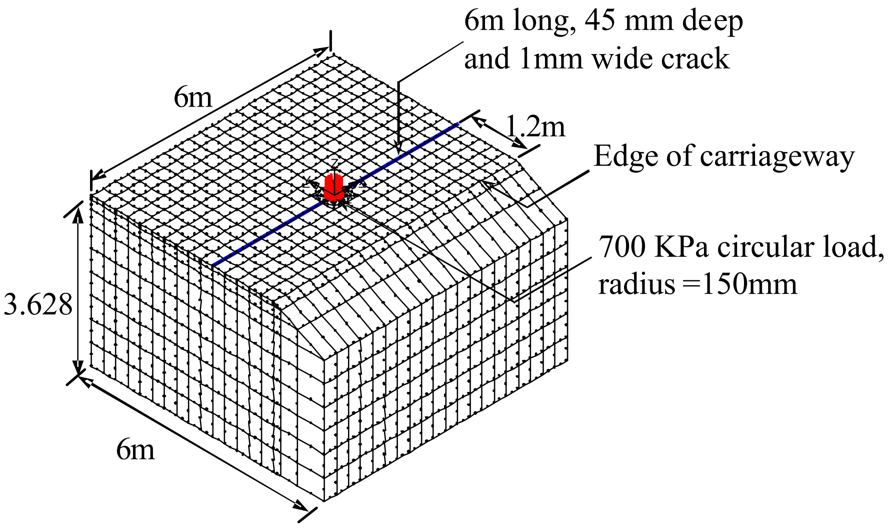

Figure 1: 3D cracked pavement model

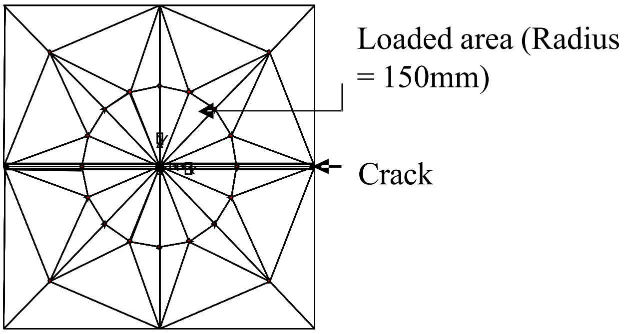

Figure 2: Plan of crack mesh at the vicinity of the loaded area

4 CALIBRATION

A back analysis was performed on the data set presented in Tables 1 and 2 to estimate the layer moduli of the models, based on actual measured deflections. The initial moduli and Poisson's ratios for the layers were selected from a data set of pavement layer moduli compiled by Evdorides (1994). This data set took into consideration in-situ conditions such as the extent of cracking and the temperature during FWD testing, which was 20°C.

The results of the convergence achieved between the measured deflection bowl adjusted to that which would have been measured under an applied stress of 700 kPa and those computed by the uncracked pavement model are presented in Figure 3 and Table 3. The calibration error of the uncracked pavement model ranged from 0% at the centre of the loading plate to -32% at a radial distance of 2100mm from the load centre, indicating a very good convergence (see Table 3). Overall, the calibration may be considered to be satisfactory for the purpose of this study. A comparison of the measured deflection bowls against those calculated from the three pavement models (i.e. that with the uncracked surfacing, the bottom-up and top-down crack) are also presented in Figure 3.

The set of the back-calculated moduli of the calibrated model is presented in Table 4. These compared well with the set of moduli of pavement layers compiled by Evdorides (1994). It may also be noted from the results that the value of the modulus of the bituminous road base is greater than that of the surfacing which corresponds with the relative thickness of the two layers (Brunton et al., 1992; Freeme et al, 1987).

Table 3: Normalized measured deflections and deflections from the calibrated model

Radial distance (mm)	0	300	600	900	1200	1500	2100
FWD normalized deflections (microns)	256	202	155	116	89	66	38
Uncracked pavement deflections (microns)	256	195	150	111	80	57	26
Calibration error (%)	0	-3	-3	-4	-10	-14	-32
Deflections calculated with modelled cracking at the top and bottom							
Bottom-up crack model deflections (microns)	257	195	150	112	81	57	26
Top-down crack model deflections (microns)	277	201	154	113	82	57	26

Table 4: Material elastic moduli and Poisson's ratio of the calibrated model

Material properties	Bituminous surfacing	Bituminous road base	Granular sub-base	Subgrade
Elastic moduli (MPa)	2000	2700	150	50
Poisson's ratio	0.35	0.35	0.35	0.35

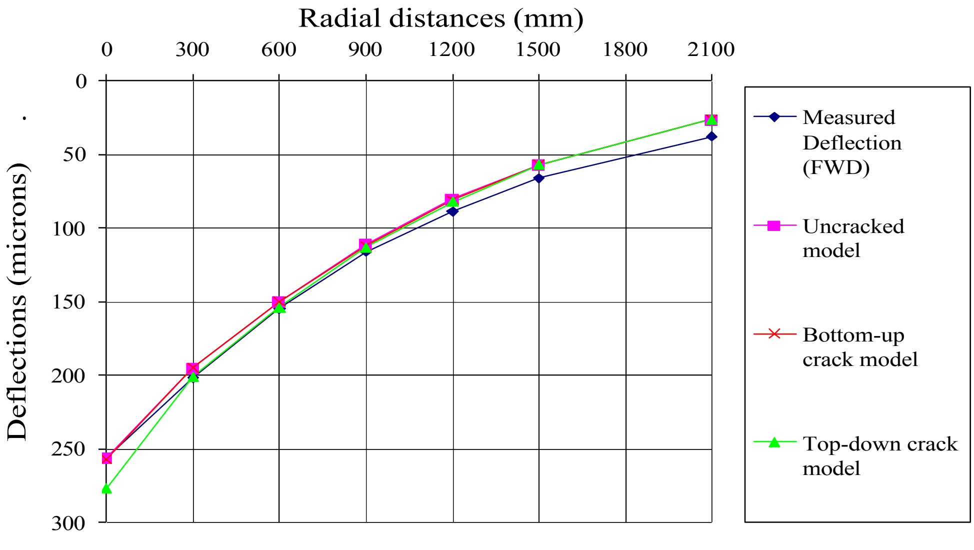

Figure 3: Normalized FWD measured deflection and FEM calculated deflections

5 STRESS DISTRIBUTION

The distribution of stresses in the bituminous layer was first studied for the three variants of the model and for the load modelled symmetrically about the crack. The distribution of horizontal and shear stresses are shown in Figures 4 through to 9. Table 5 summarises the maximum stresses calculated in the bituminous layers of the uncracked, top-down crack and bottom-up crack models. It may be observed that, whereas the introduction of a single top-down and bottom-up crack did not significantly affect the deflections of the pavement, significant changes in the maximum stresses may occur (Table 5).

The shearing effect of the loading applied asymmetrically about the crack was then investigated by plotting the shear stresses at the surface of the bituminous surfacing, the crack tip plane, and the bottom of the bituminous road base. The shear stress plots are shown in Figures 10 through to 12. In these, the cross section of the cracks is located at a distance of 0m, while the centre of the loading plate is located at 0.15m.

Table 5 Maximum stresses (kPa) in bituminous layer

Models	Stresses (kPa)			Location
Uncracked model	σ_y	Tensile	177	Bottom of bituminous road base
		Compressive	-628	Surface of bituminous layer, at the mid-point of loaded area
	σ_z	Tensile	66	Surface of bituminous layer, at a distance of 0.3m from load centre
		Compressive	-703	Surface of bituminous layer, at the mid-point of loaded area
	σ_{yz}	Tensile	170	Bottom of bituminous surfacing, below the edge of loading plate
		Compressive	–170	Bottom of bituminous surfacing, below the edge of loading plate
Model with Top-down cracking	σ_y	Tensile	202	Bottom of bituminous road base
		Compressive	-801	Vicinity of crack tip
	σ_z	Tensile	73	Surface of bituminous layer at radial distance of 0.3m from centre of loaded area
		Compressive	-770	Vicinity of crack tip
	σ_{yz}	Tensile	327	Vicinity of crack tip
		Compressive	–327	Vicinity of crack tip
Model with Bottom-up cracking	σ_y	Tensile	211	Bottom of bituminous surfacing layer
		Compressive	-2056	Bottom of crack/bottom of bituminous surfacing layer
	σ_z	Tensile	104	Bottom of crack/bottom of bituminous surfacing layer
		Compressive	-2412	Bottom of crack/bottom of bituminous surfacing layer
	σ_{yz}	Tensile	272	Bottom of crack
		Compressive	–272	Bottom of crack
Notes: σ_y = Horizontal stress, σ_z = Vertical stress, σ_{yz} = Shear stress, (-) = Compressive stress, (+) = Tensile stress				

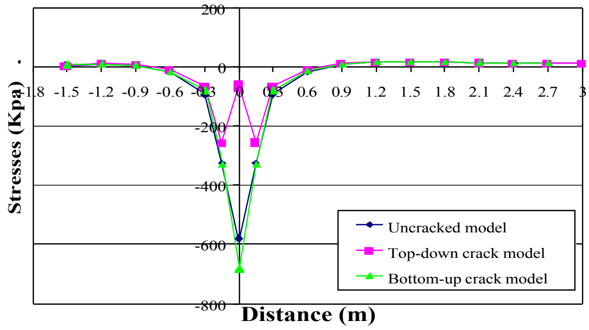

Figure 4: Horizontal stresses at the surface of the bituminous surface layer

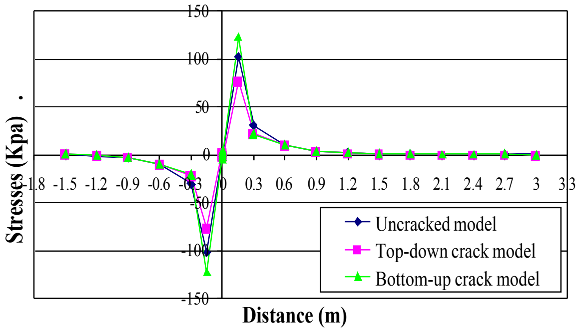

Figure 8: Shear stresses at the middle (crack tip plane) of bituminous surface layer

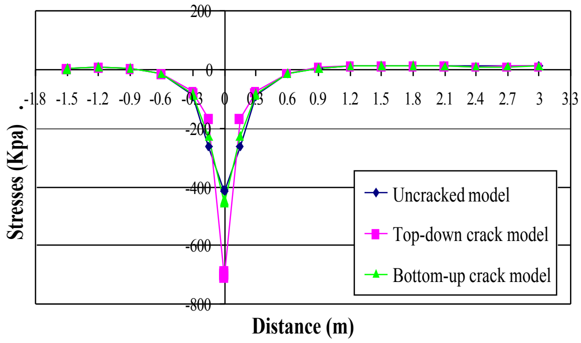

Figure 5: Horizontal stresses at the middle/crack tip plane of bituminous surface layer

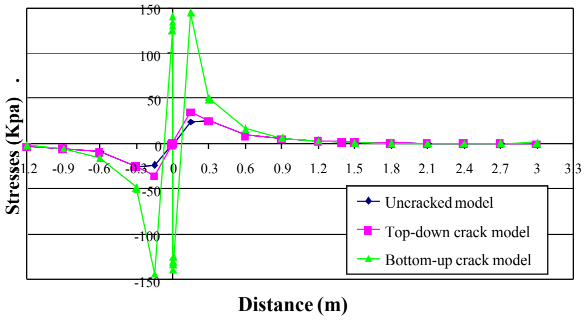

Figure 9: Shear stresses at the bottom bituminous surface layer

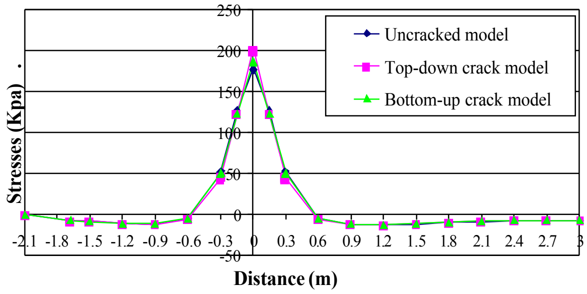

Figure 6: Horizontal stresses at the bottom of the bituminous surface layer

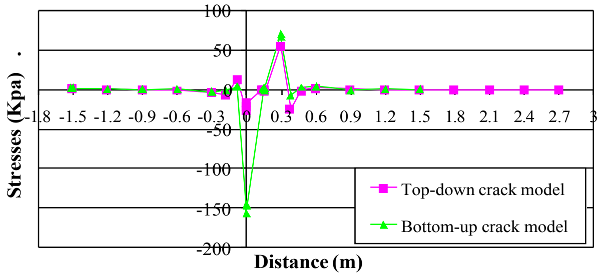

Figure 10: Shear stresses at the surface of bituminous layer due to asymmetrical load

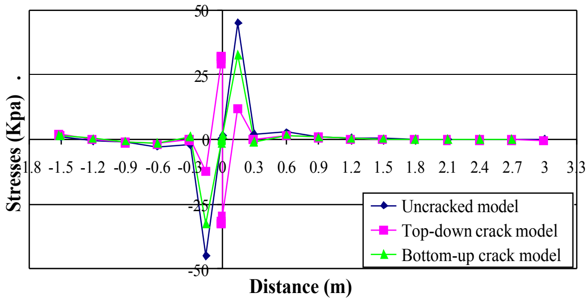

Figure 7: Shear stresses at the surface of the bituminous surface layer

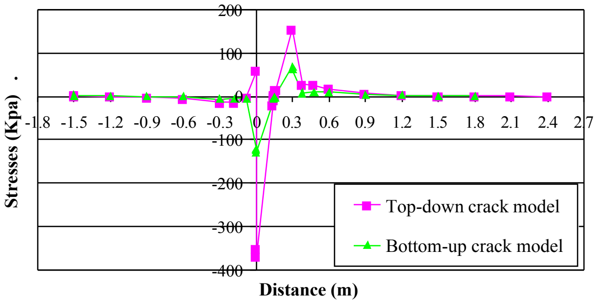

Figure 11: Shear stresses at the crack tip plane of bituminous layer due to asymmetrical load

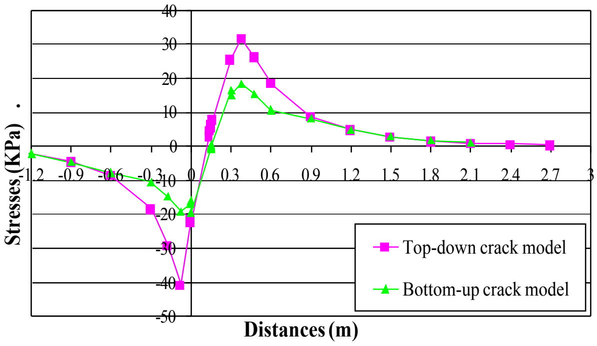

Figure 12: Shear stresses at the bottom of the bituminous layer due to asymmetrical load

6 DISCUSSION

This paper presented a 3D FE model of a pavement and investigated the effect of single cracks on the distribution of load-induced stresses.

FE methods have long been used for the analysis of pavements, as they are powerful and versatile tools. However they should be used with care as they may produce erroneous results due to the influence of a number of factors inherent in the simulation process. 3D FE models appear to provide a more accurate representation of the structures and, as a consequence, the results of the analysis may be more reliable compared to those of 2D or axisymmetric models. In addition, their versatility allows the simulation of complex structures and loadings, such as that of wheels of vehicles or aircrafts, or the investigation of phenomena that cannot be satisfactorily represented in the 2D space or by using cylindrical co-ordinates.

However, a number of parameters may affect the accuracy of the computations. These include the size and configuration of the FE mesh, the type and number of elements, the boundary conditions and the approximations of the theory that the FE method uses. The use of a general-purpose FE package like LUSAS would seem to minimise the effect of all these parameters but still it was necessary to follow a systematic approach to modelling. As far as the mesh used in the models presented herein is concerned, the selection of its size was based on previous analytical work (Evdorides, 1994). The configuration of the mesh was influenced by the use of hexahedral elements in the general case, but a different local mesh was developed for the vicinity of the loading area. The number of elements did not seem to affect the computations significantly and therefore it was felt desirable to keep them to a minimum (except for those at the vicinity of the loading area and the cracks) so that the computation time could be reduced. This time was approximately 15 min on the computer used.

In addition to the above, any FE analysis is affected by the theory on which it is based. In this work a linear elastic model was used. This is associated with a number of approximations but offers a reasonable approach when the moduli of the layers are carefully selected (Brown et al., 1985). But even with such a simplified approach the effort required to set up, run and assess the results of the 3D FE analysis is considerable and therefore it seems that such an approach should not be attempted for routine analyses. However, it is felt that the 3D modelling offered a strong tool that enabled an insight into the pavement response to loading.

Any such analysis heavily relies on a calibration to in-situ conditions. In this work, the calibration resulted into a good convergence between the measured and computed deflections. Its success may be attributed to the appropriate selection of the initial material moduli, the accuracy of the computer program used and the expertise of the analyst. However it should be noted that the back analysed moduli computed by a 3D model may be different from those from a 2D model (Anyala, 2004) but a further investigation was beyond the scope of this paper.

Based on the assumption that the calibration of the 3D model provided an accurate simulation of the pavement behaviour, a number of observations may be made for the deflections and the stress distribution in the three pavement models considered.

As far as the deflections are concerned, it was interesting that the presence of a single crack (either bottom-up or top-down) did not significantly affect the computed deflections. This indicates that, at least from a theoretical point of view, the validity of any back analysis results may be questioned unless they are in agreement with additional information obtained from either field or laboratory testing. The effects of possible errors in the back analysis may be further influence the selection or design of maintenance treatments.

With regard to the stress distribution, an examination of the results from the three models shows that the presence of cracking affects the magnitude of the stresses and the location of where the maximum stresses occur. As fatigue is associated with tensile stresses, their distribution was examined further. For the models at hand, the tensile stresses at the surface and bottom of the bituminous surfacing were not significantly affected by the presence of the cracks (see Figures 4-6). However there was a significant change in the shear stresses (perpendicular to the direction of the crack) when a crack was present. At the surface of the pavement the shear stresses were higher when the surfacing was uncracked whereas they were higher in the middle and bottom of the surfacing when a crack was present. Bottom-up cracking seemed to cause a significant increase in the shear stresses at both locations. A further investigation of the shear stress regime was carried out using a model with asymmetrical loading about the edge of the crack. The analysis showed that compared with the case of symmetrical loading, bottom-up cracking caused an increase in the shear stresses at the surface of the pavement and top-down cracking caused an increase in the shear stress in the middle of the layer. However, asymmetrical loading induced lower shear stresses at the bottom of the surface layer than that caused by symmetrical loading.

From the above it may be seen that the presence of a single crack may affect (a) the tensile stresses in bituminous surfacings to a small extent and (b) the shear stresses to a significant extent. The influence of bottom-up cracking is higher than that of top-down cracking, but that of the latter should not be overlooked. Indeed further work is needed to provide a better understanding of the behaviour of cracked pavement layers under traffic loading. It is necessary however that the modelling of cracking should be further enhanced to include other aspects such as the bonding and interaction between the pavement layers. General-purpose FE packages like LUSAS appear to provide both an accurate computational environment and the tools that facilitate the analyses sought.

7 CONCLUSIONS

This paper has presented simple 3D models for the analysis of cracked bituminous layers. Both bottom-up and top-down cracking were considered and simulated accordingly. The analysis showed that single top-down or bottom up cracks in pavement bituminous layers do not have a significant effect on the surface deflection. Rather they may significantly affect the load induced stress regime. A comparative examination of the stresses developed at the vicinity of single bottom-up and top-down cracking indicated that the effect of top-down cracking on the pavement response should not be overlooked as it may lead to fatigue failure like bottom-up cracking.

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