Simulation Of The Response Of Cracked Flexible Pavements To Surface Loads

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ABSTRACT

Flexible pavements frequently show a loss of stiffness prior to any visible surface distress or marked loss of serviceability. This loss of stiffness is detected by stationary, or very slow moving, devices such as the Falling Weight Deflectometer or Deflectograph. The loss of stiffness is frequently linked with the growth of fatigue cracks from the bottom of the pavement's bound layers towards the surface.

This paper contains finite element simulations of the response of cracked pavements to loads applied to their surfaces where, in practice, only the surface deflections can be monitored. The aim is to investigate whether single cracks originating from the bottom of the bound layers can be detected by the response at the surface and under what loadings.

INTRODUCTION

It is common practice to use surface deflection methods to assess the structural condition of a pavement. In the UK the most common systems in use are the Deflectograph and Falling Weight Deflectometer. Both of these methods aim to identify "the loss of structural strength due to repetitive loading causing cracking and deformation and consequently ingress of water" [1]. However, as the strength (stiffness) of asphalt is very dependent on its temperature it is necessary to correct the measured deflections for temperature. This variation of surface deflection with parameters other than structural condition leads to a range of interpretations of any particular set of measurements.

When simulations of these tests have been made, they have generally been carried out with programs that assume that the pavement is uniform in its material properties along any horizontal plane. The modelling of structural degradation is therefore interpreted as a reduction in the stiffness of the layers where the cracking is taking place.

This averaging-out of the effect of cracking through the layer disguises one property of a crack in the pavement that makes it distinct from a reduction in stiffness due to temperature effects. The presence of a crack in a pavement leads automatically to a pavement response that varies as the crack itself is traversed by a load. If it is possible to detect these variations in response with position of load then it may be possible to infer the presence of a crack directly from the results, and distinguish it from an increase in response due to changes in temperature.

Pavements with cracks have been analysed before [2–5] but the focus of these studies has been the growth of cracks in pavements and not their detection. The theory used, therefore, concentrates on analysis of stress concentrations around crack tips, and does not easily give rise to analysis of surface deflections.

One recent study has investigated the effects of cracks on pavement deflections using finite element analysis (FEA) [6]. The cracks, however, penetrate the full depth of the asphalt layers, giving large effects on the measured deflection.

The aim of this paper is to investigate the changes in surface deflections that might be caused by the appearance of a crack at the bottom of the asphalt layers without penetrating the surface, and to investigate what sort of surface loadings might be used to enhance the ease of detection of cracks.

CRACKED PAVEMENT MODELS

THE PAVEMENTS

Two basic pavement constructions have been investigated. Pavement A would be typical of a minor road and pavement B a motorway in the UK.

Both of these pavements were analysed using two-dimensional, static, plane strain FEA with a range of different crack sizes and configurations. This simplified model would not be replicated in practice, but it has been shown [7] that simplified, two-dimensional pavement models can give good simulations of the true three-dimensional case.

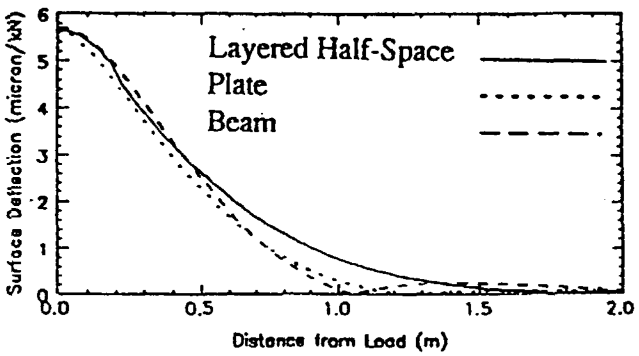

Figure 1a. The responses of pavement A from other simulations [7]

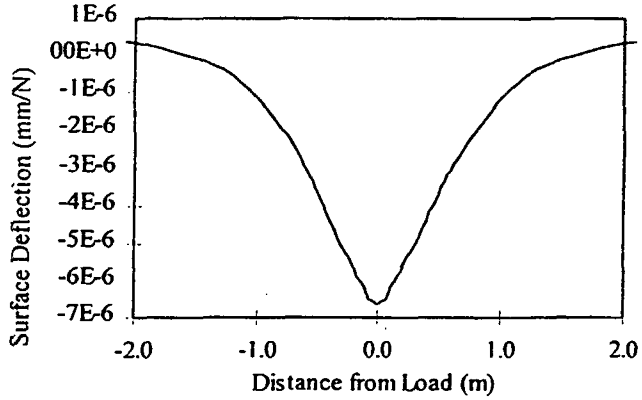

Figure 1b. The FEA response of pavement A.

Previous studies have shown that the response of a pavement to oscillating or moving loads is smaller than the response to a static, stationary load [8].

The material parameters chosen for the models here were those fitted to real responses at low (between zero and 10Hz) frequencies [9] when the load is not travelling over the surface. Whilst this may not be ideal for finding the response of this particular pavement to moving loads, the range of stiffnesses that are possible for asphalt mixtures, and the variation that can be found with varying temperature during the day, obviates the need to characterise any particular pavement more accurately.

The FE mesh generated for the analysis contained a total of 768 8-noded quadratic elements with a high concentration of elements around the crack, especially the crack tips. In practice, however, only surface measurements can be made on roads and, as long as the crack does not approach the surface too closely St Venant's Principle indicates that precise modelling in the region of the crack tips does not have a serious effect on the surface deformation, as long as the overall effect of the crack is modelled adequately.

The model extends to 10m each side of the crack, where it is restrained to move only in the vertical direction. There was negligible movement at this distance under any of the loading conditions examined. The base of the model was restrained in both horizontal and vertical directions.

Table 1. Pavement specifications

	Young's modulus/MPa	Poisson's ratio	Depth/m
Pavement A			
Asphalt layers	3 000	0.35	0.2
Foundation	140	0.4	1.9
Pavement B			
Asphalt layers	3 000	0.35	0.4
Foundation	140	0.4	1.9

The load is applied uniformly over a 200mm wide strip. This is likely to give an overestimate of the true surface deflections as the load in this model extends infinitely, rather than just over a small patch of the road surface.

The model parameters for the minor road (pavement A) were taken from a previous investigation into modelling road responses [7]. The parameters for the motorway construction (pavement B) are based on the material properties obtained from the minor road model, but with the asphalt thickness increased to typical UK motorway standards. The material parameters and geometry of the models are shown in table 1.

The surface deflections due to vertical surface loads obtained using FEA for pavement A with no crack compare favourably with those predicted for this pavement by other verified models (see figure 1). There is a small increase in the peak response which may be attributable to the plane strain model used here with no adjustment for the cylindrical symmetry of the real loading, as described above.

EFFECT OF CRACK GEOMETRY

When a crack appears at the bottom of the asphalt layers it will effectively grow both upwards into the asphalt layers and also downwards into the granular layers. If this downward growth did not occur there would be a large tensile stress concentration at the interface of the asphalt and granular layers. A granular material is unable to sustain tensile stresses so the material must be pulled apart, forming a downward propagating crack. This section investigates the size of this crack and the sensitivity of the surface deflection to its correct modelling.

Cracks extending parallel with the interface of granular and asphalt layers were also simulated, but is was found that these delaminating cracks are held closed by the application of vertical surface loads, and therefore sliding between the layers will be limited by friction.

In order to investigate the effect of vertical crack penetration into the granular layers, pavements A and B have been analysed with a crack penetrating 100mm into the asphalt, and a variety of depths into the sub-base: 10, 30, 60 and 150mm. These pavements are referred to as A100/10, A100/30, A100/60, A100/150, B100/10, B100/30, B100/60, and B100/150.

Figure 2 shows the deviation in response of models A100/30, A100/60 and A100/150 from A100/10. These differences are approximately 1% of the total observed deflection for the uncracked road showing a lack of sensitivity to this depth of penetration.

Figure 3 shows the deviation of models B100/30, B100/60 and B100/150 from the B100/10 response. Again these differences are less than 1% of the total observed deflection for the uncracked road (see figure 5 below).

In the rest of this paper the crack penetration into the granular layers has been fixed at 100mm. The penetration into the asphalt layers is varied for the two pavements giving a total of nine different pavements for consideration. These are referred to by the letter identifying the pavement construction (A or B) and the penetration of the crack into the asphalt layers *e.g.* Pavement B150 is pavement B with a crack penetrating the asphalt layer by 150mm.

RESPONSE TO VERTICAL LOADS

CENTRALLY APPLIED LOADS

When a vertical load is applied directly over a crack in a pavement the crack will open up and the deflection of the surface of the road will be larger than that found for an uncracked pavement.

The deflection under the load for the nine pavements are shown in figures 4 and 5. The deflection increases as the crack grows, as expected, by as much as 20% for cracks that are severe. However, it may be very difficult in practice to distinguish between the increase in deflection due to the crack compared with the changes due to temperature, for example.

Figure 2 shows the deviation in response of models A100/30, A100/60 and A100/150 from A100/10. These differences are approximately 1% of the total observed deflection for the uncracked road showing a lack of sensitivity to this depth of penetration.

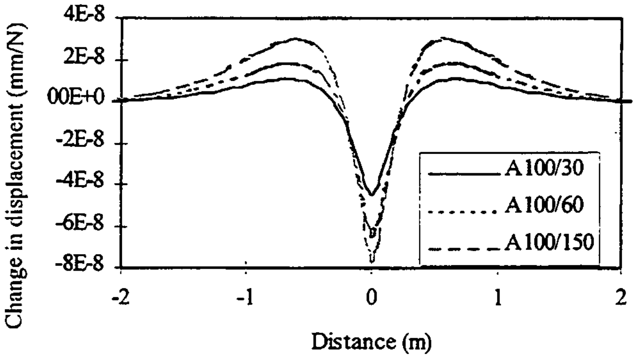

Figure 2. Change in pavement A responses with crack penetration into the granular layers.

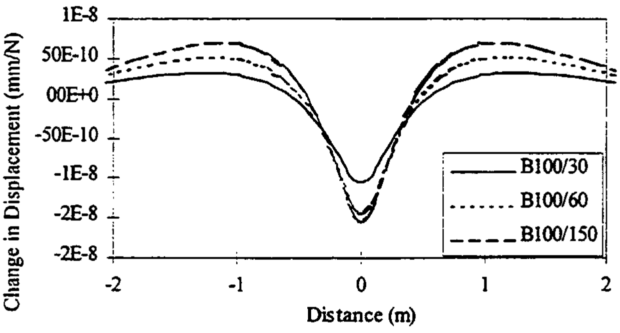

Figure 3. Change in pavement B responses with crack penetration into the granular layers.

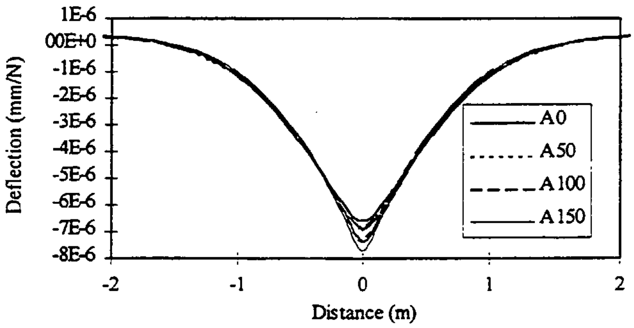

Figure 4. Pavement A responses to loading over a crack.

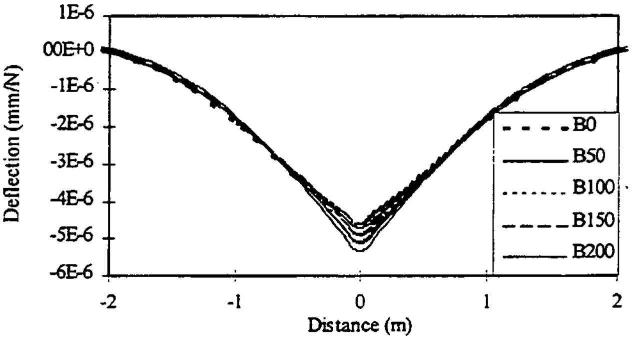

Figure 5. Pavement B responses to loading over a crack.

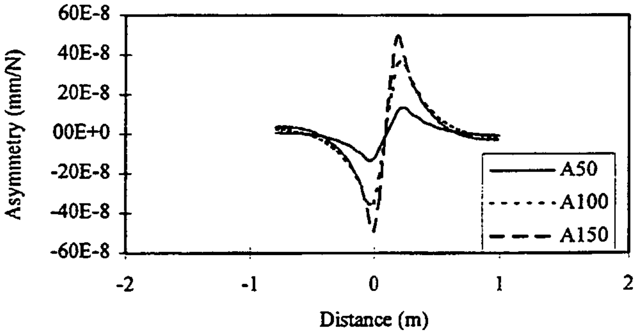

Figure 6. Asymmetry in pavement A response caused by a crack 100mm from the load

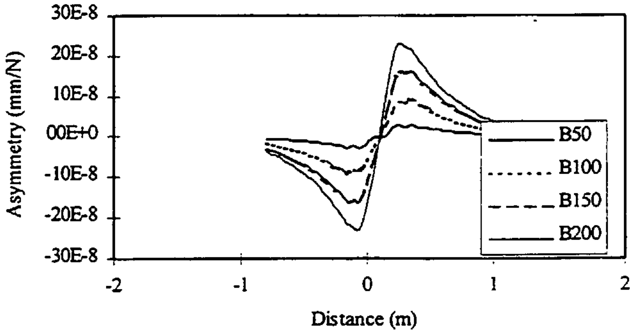

Figure 7. Asymmetry in pavement B response caused by a crack 100mm from the load.

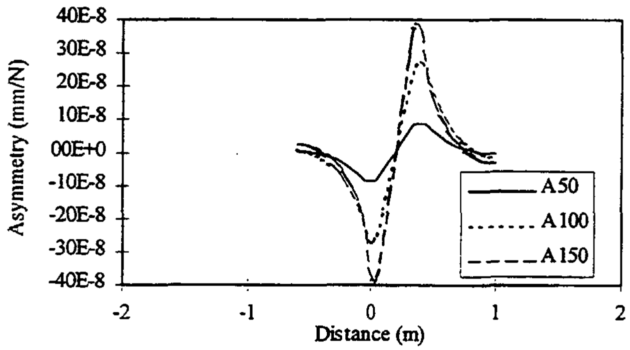

Figure 8. Asymmetry in pavement A response caused by a crack 200mm from the load

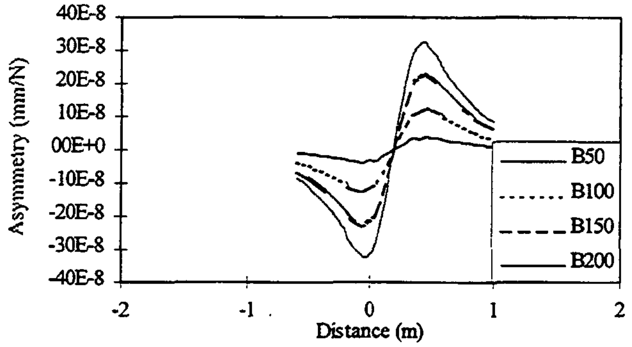

Figure 9. Asymmetry in pavement B response caused by a crack 200mm from the load

NON-CENTRAL LOADS

When a vertical load is applied to one side of a crack in a pavement the crack may open up, giving rise to a response that is not symmetrical about the load, or it may close which will then give the same response as an uncracked pavement. Whilst changes in the maximum deflection under the load may be difficult to distinguish from environmental influences over the time of the crack growth, it may be possible to identify the changes in symmetry that occur due to the existence of a crack. Figures 6 to 11 show the asymmetry in the cracked road responses for loads applied at distances 100mm, 200mm and 500mm from the crack. In all figures the horizontal axis is measured from the crack and the load is moved to the right. The asymmetry is defined to be the response to the load minus the response reflected about the load. If there was no asymmetry in the response the response and its reflection would be identical and the plot would show a zero, horizontal line.

When the load is close to the crack, as in figures 6 and 7, the load tries to open the crack and the deflection at the crack is larger than the symmetric deflection on the other side of the load. Whilst the changes in response are still small compared with the overall response, especially for pavement B with small cracks, the asymmetry produced may be more reliably detected than the overall change in response that might be expected.

Figures 8 and 9 show the asymmetry produced when the load is 200mm from the crack. The responses are very similar in magnitude to the responses when loaded at 100mm. This lack of sensitivity to distance of the load from the crack is to be expected as there is no asymmetry when the load is directly over the crack or when the load is a long way from the crack.

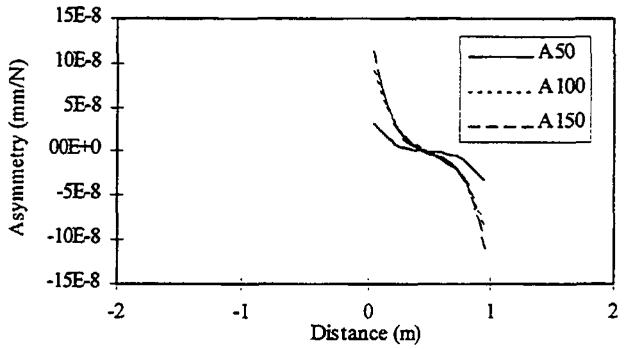

Figure 10. Asymmetry in pavement A response caused by a crack 500mm from the load

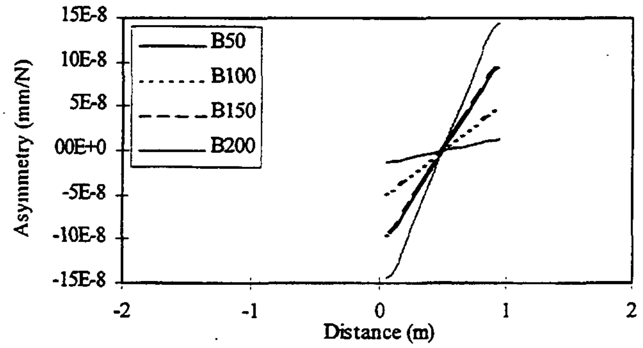

Figure 11. Asymmetry in pavement B response caused by a crack 500mm from the load

Figures 10 and 11 show part of the response when the load is 500mm from the crack. The analysis when the load is this far from the crack is limited due to the construction of the FE mesh and the software used. However, the small part of the response shown is quite illuminating. In figure 10 the response appears to go positive to the left of the load, unlike the responses from this pavement when the load was closer to the crack. Further examination of this case reveals that the crack is in fact closing. The FE model does not have any contact elements, and therefore this case appears to show the road overlapping itself as the crack opening becomes negative. This is clearly nonsense. A correct interpretation when the crack appears to close is that the response would be the same as for the uncracked road and no asymmetry would result.

When pavement B is loaded in this way, however, the crack is still observed to open and could be detected by the asymmetry.

Whilst the asymmetry in the cracked pavement responses are of similar magnitude to the changes observed in the centrally loaded case, the differences are more clearly identified in these cases because no reference is needed to a response that must be theoretically derived or recorded from the undamaged pavement.

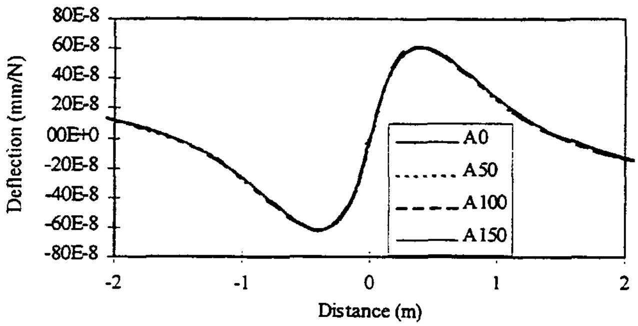

Figure 12. Vertical deflection of pavement A subjected to a shear load over the crack.

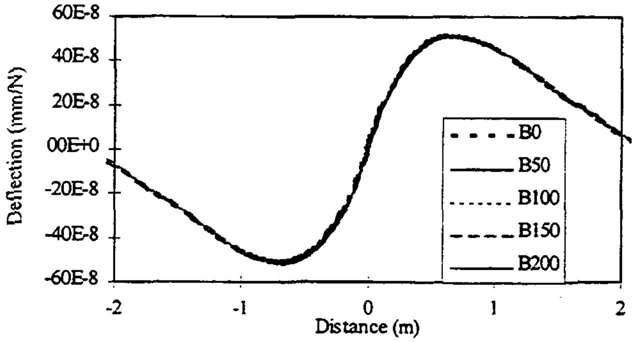

Figure 13. Vertical deflection of pavement B subjected to a shear load over the crack.

RESPONSE TO SHEAR LOADS

In order to investigate how the effect of the crack can be exaggerated, the responses to surface shear loads have been investigated. It was hoped that shear loads opening a crack when applied in one direction but closing it when applied in the reverse direction could be used more effectively than the simple vertical loads which may or may not open the crack. The practicalities of applying these loads are discussed in a later section of this paper.

When a shear load is applied directly over a crack there is no tendency to open or close the crack at all because of the symmetry of the situation. There is a tendency to produce shear motion across the crack and in practice this would be resisted by friction. The largest difference in response to different crack sizes will be produced when the coefficient of friction is zero. The responses of the two pavements to shear loads applied directly over the crack and to the right, are shown in figures 12 and 13.

For both pavements there is barely any visible effect of increasing crack size. The deflections are also small compared with the deflections due to vertical loads (approximately 1%).

When loads are applied to one side of the crack there will be a tendency for the crack to either open or close, depending on the location and direction of the load and the size of the crack. Figures 14 to 19 show the response of the cracked pavements minus the response of the uncracked pavement in each case.

Figure 14 shows that there is more deflection at the crack for a load 100mm away when the crack is 50 or 100mm into the asphalt. However, when the crack is 150mm (¾ of the way through the asphalt) the response between the crack and the load is increased, but the response beyond the crack is reduced.

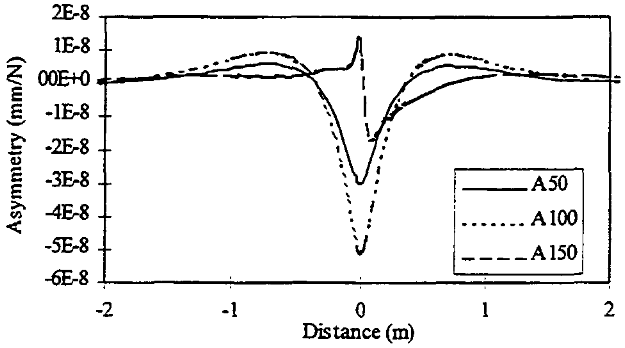

Figure 14. Asymmetry in pavement A response caused by a crack 100mm from a shear load

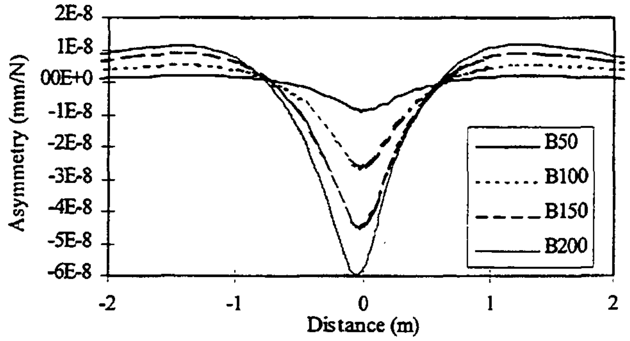

Figure 15. Asymmetry in pavement B response caused by a crack 100mm from a shear load

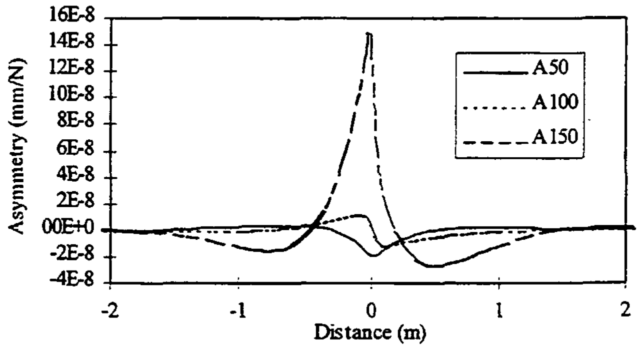

Figure 16. Asymmetry in pavement A response caused by a crack 200mm from a shear load

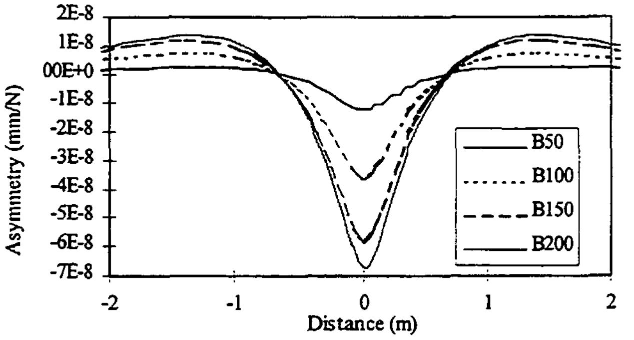

Figure 17. Asymmetry in pavement B response caused by a crack 200mm from a shear load

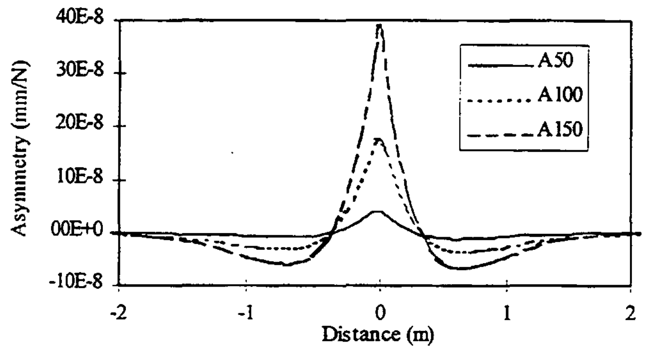

Figure 18. Asymmetry in pavement A response caused by a crack 500mm from a shear load

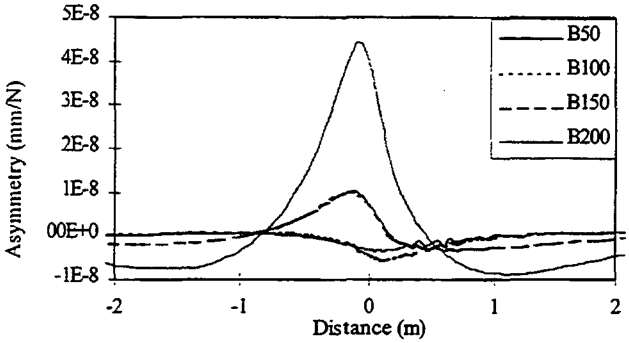

Figure 19. Asymmetry in pavement B response caused by a crack 500mm from a shear load

This lack of response of a damaged pavement can be explained by the fact that the load is not fully transferred beyond the crack. The lack of response is therefore not a reaction to strengthening by the crack but a response to lack of load transfer beyond the crack.

All the other responses show increased deflection in the region of the crack, with the responses increasing with crack size. The asymmetry observed is up to 10% of the total deflection.

Figures 16 and 17 show the same responses but with the load 200mm from the crack. Again the anomalous results for pavement A100 can be explained by a lack of load transfer across the crack.

The reponse of pavement A100 is similar to the responses when the load is 500mm from the crack and these are discussed below.

The lack of load transfer effect is not apparent on the stiffer, deeper pavement B until loads 500mm from the crack are examined.

The responses to loading 500mm from the crack are shown in figures 18 and 19. In both these simulations there is now a tendency for the crack to close rather than open. As discussed above, this cannot occur. However, in contrast to the vertical loading case above, it is possible to reverse the load direction when this happens due to shear loads and maintain an open crack giving asymmetry. The results presented here are therefore possible, but should be considered in the context of a reversed load.

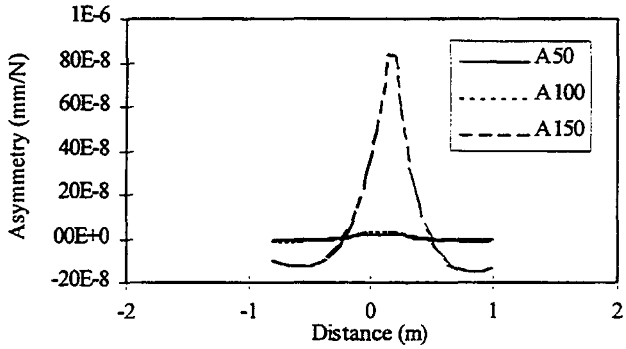

Figure 20. Asymmetry in pavement A response caused by a crack 100mm from a combination of loads

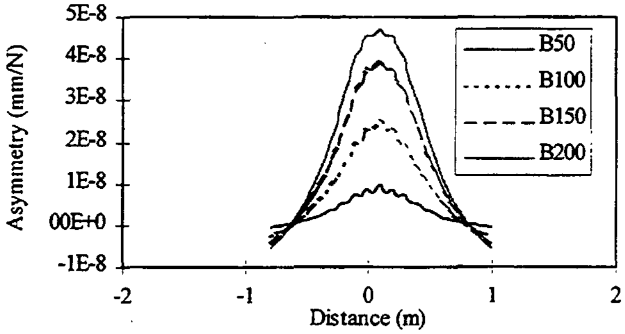

Figure 21. Asymmetry in pavement B response caused by a crack 100mm from a combination of loads

PRACTICAL IMPLEMENTATION

It is not practicable to apply a shear load to a pavement in isolation of a vertical load. The coefficient of friction between a tyre and a dry road can be as high as 0.8 [10] and it is therefore possible to generate combined lateral and vertical loads in the road by, for example, using a misaligned wheel running on a vehicle.

If two wheels were directed at opposite yaw angles to the same line of travel, one of the tangential forces will tend to close the crack, whilst the other will tend to open it (unless both wheels pass directly over the crack). If the crack closes then the response will be the same as the road in its undamaged condition. A third wheel running along the same line of travel but aligned with it could also be used to assist in the analysis of the responses.

If a pavement is not cracked then the response to a tangential load can be calculated from the response to a combined tangential and vertical load and the response to a vertical load. If two different combined loads are analysed with the tangential components equal and opposite then the tangential component of the response will be equal and opposite, and antisymmetric about the load.

The cracked roads have been simulated with a vertical load and with a combined vertical and tangential load. The tangential load is half the magnitude of the vertical load, *i.e.* mobilising a friction coefficient of 0.5. The tangential components have been applied both towards and away from the crack. Under each of these loadings the crack has been

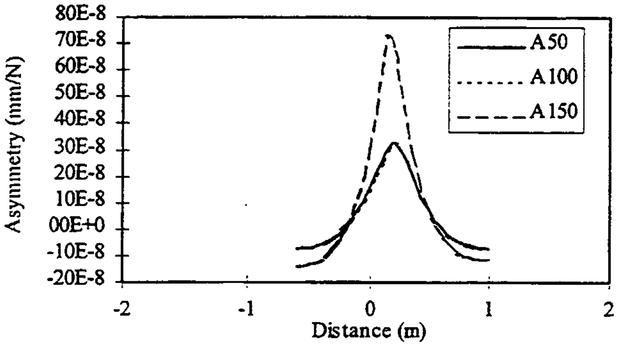

Figure 22. Asymmetry in pavement A response caused by a crack 200mm from a combination of loads.

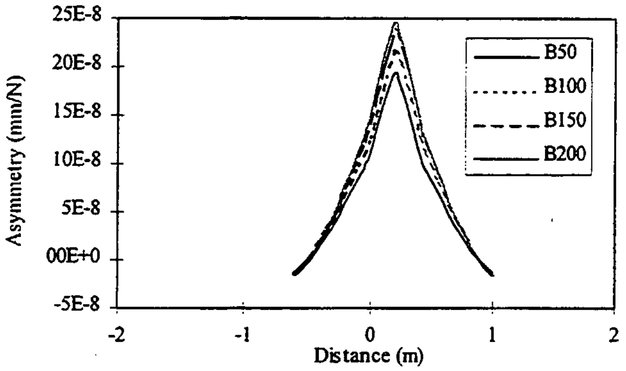

Figure 23. Asymmetry in pavement B response caused by a crack 200mm from a combination of loads.

examined and the response of the uncracked pavement has been substituted if the crack appears to close.

The responses to the tangential components of the load have been calculated as described above and the difference between the theoretically perfectly antisymmetric responses found. The asymmetry discovered is due to the opening or closing of the cracks under the three different loading conditions. The asymmetry discovered in this way could be used in practice as these loads are all possible to apply to a road surface.

Figures 20 and 21 show the asymmetry of the two pavements when analysed in this way when loaded 100mm from the crack. The asymmetry observed is of similar magnitude to that observed when the shear load alone is used except for the response of pavement A with a 150mm crack. This gave an almost discontinuous response when loaded with a shear load alone. With this combined load analysis the response is more continuous as the crack is opened by the vertical load with the shear loads not managing to close it when acting in either direction.

Figures 22 and 23 show the asymmetry when the load is 200mm from the crack. As with the shear loading alone, there is an increase in the asymmetry compared with the previous results.

Figures 24 and 25 show the asymmetry when the load is 500mm from the crack. The asymmetry is still very large at this distance from the crack and is greater than 10% of the deflection measured under a single vertical load.

Such large deviations over such a wide range of distances from a crack make investigation and implementation of this sort of analysis more practicable. There are obvious advantages over existing practice with the penalty of mush more complex loading arrangements.

CONCLUSIONS

1. FEA can be used to investigate the effects of cracks on the surface response of pavements. Two dimensional plane strain models may overestimate the true response of the pavement, but are useful for examining trends and investigating the initial feasibility of crack detection.
2. When a cracked pavement is loaded vertically at a distance from the crack, there is a possibility of the crack opening up and producing an asymmetric response. The crack may, however, alternatively be pressed closed by the load and a symmetric response would result. An asymmetric response may be used to identify a crack, but a symmetric response to vertical loads does not indicate that no crack is present.
3. Shear loads at the surface give rise to antisymmetric responses if the load is over the crack. If the load is not over the crack the response will not be antisymmetric if the crack opens and the presence of a crack can be detected by the asymmetry.
4. For some pavement constructions, loadings and crack

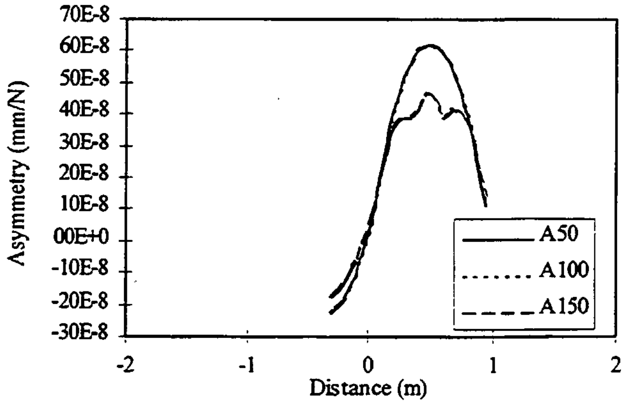

Figure 24. Asymmetry in pavement A response caused by a crack 500mm from a combination of loads

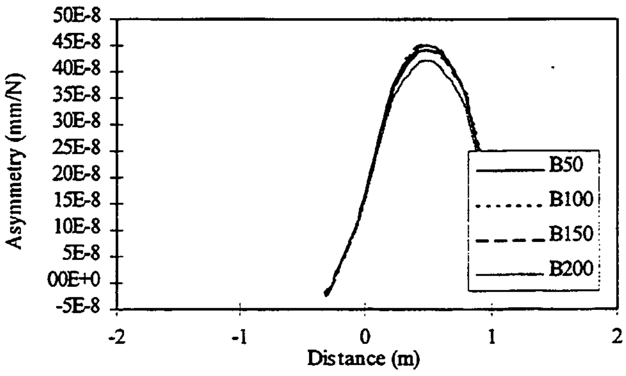

Figure 25. Asymmetry in pavement B response caused by a crack 500mm from a combination of loads

geometry there is a tendency for the crack to close. This results in a symmetric response. The asymmetry can be returned by reversing the shear load causing the crack to open.

5. Vertical or combined vertical and shear loads can be applied to the road in practice. Analysis of the response to a vertical load, and a vertical load combined with shear loads in both directions can reveal asymmetry due to the presence of a crack.
6. Over a wide range of distances and crack sizes, combined loads can reveal large asymmetries in response indicating the presence of cracks. These asymmetries will be revealed by the combination of loads even if some loads close the crack and others open it.
7. Further work is required to investigate more realistic three-dimensional loading conditions for a larger range of pavements. An experimental investigation into the technique is also required before much further progress can be made.

REFERENCES

1. Anon, *'Bituminous mixes and flexible pavements - an introduction'* British Aggregate Construction Materials Industries, London, 1992.
2. Folias, E.S., *'On a plate supported by an elastic foundation containing a finite crack'* Int. J. Fracture Mechanics, Vol.6, No. 3, Sept., 1970.
3. Wnuk, M.P., *'Subcritical growth of fracture (Inelastic fatigue)'* Int. J. Fracture Mechanics, Vol.7, No. 4, Dec., 1971.
4. Lin, S-T., Folias, E.S., *'On the fracture of highway pavements'* Int. J. Fracture Mechanics, Vol.11, No. 1, Feb., 1975.
5. Ramsamooj, D.V., *'Fracture of highway and airport pavements'* Engineering Fracture Mechanics, Vol.44, No..4, pp.609–626, 1993.
6. Uddin, W., Zhang, D., Fernandez, F., *'Finite element simulation of pavement discontinuities and dynamic load response'* TRR 1448, TRB, 1994.
7. Hardy M.S.A., Cebon, D., *'Flexible pavement response models for assessing dynamic axle loads'* Heavy vehicles and roads:technology safety and policy, Proc. 3rd Int. Symp. Heavy Vehicle Weights and Dimensions, University of Cambridge, UK, 1992, ed. D. Cebon & C.G.B. Mitchell, pub. Thomas Telford, London.
8. Hardy M.S.A., Cebon, D., *'Importance of speed and frequency in flexible pavement response'* J. Eng. Mechanics, ASCE, Vol.120, No.3, Mar. 1994.
9. Hardy M.S.A., *'Response of flexible pavements to dynamic tyre forces'* PhD thesis, University of Cambridge, UK, 1990.
10. Ervin RD, *'Measurements of the longitudinal and lateral traction properties of truck tires.'* Braking of road vehicles, IMechE, London, 1976.

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