Assessment of the interfacial stresses in a composite highway surfacing under heavy goods vehicle loading

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This paper investigates the interfacial stresses induced on the chippings and binder at different levels of surface microtexture. It describes how a Computer Aided Testing dynamic measurement system was set up to measure the contact stresses between a moving tyre and the road surface. The subsequential interfacial stresses induced between the chipping and the matrix were analysed and a mathematical model developed. The findings not only enable engineers to analyse the stresses which may be causing the pavement surface to polish but they also enable the designer to select the correct binder characteristics, the binder content in the composite material and the optimum surface macrotexture to prevent the premature removal of chippings due to interfacial stresses induced by the dynamic loading by modern heavy goods vehicles.

1. INTRODUCTION

The axle weight of a heavy goods vehicle is one of the most important factors in the design of a pavement structure, based on a standard axle load assumed to be evenly loaded over a circular area and the assumption that the resultant contact stresses acting on the road surface are constant. Many types of premature pavement surface failures, such as stripping or disintegration of the surface and polishing of the pavement surface, are not due to the failure of a pavement structure as they only occur at the surface of a pavement. Surface dressing failures are obvious examples of this type of failure. Unlike structural failures in a pavement, many surface failures are directly connected with the dynamic contact stresses occurring between moving tyres and a pavement surface rather than the axle weights of traffic. An assessment of the effects of dynamic contact forces on pavement surfaces is likely to be of benefit in the analysis of a surfacing failure and in pavement design.

However, the materials in a hot rolled asphalt surfacing is a most complex composite consisting of coarse and fine mineral matter, filler and a bituminous binder. The binder, filler and fine mineral matter combine to form a mortar with the coarse aggregate dispersed within the matrix. Mixes are consequently expressed in terms of their coarse aggregate content. Then pre-coated chippings (usually 14 mm or 20 mm in size) are rolled into the running surface of the roadway to provide texture depth for skid-resistance purposes. In the case of surface dressing, the process involves the spraying of a hot binder unto the existing road surface and covering with aggregate chippings, thus providing a new and supposedly improved road surface. In both conditions, the actual interfacial stress between chippings and the binder induced by dynamic contact force is a crucial factor in achieving aggregate retention.

To overcome these problems, the authors considered it essential to investigate the distribution of the contact stresses at the interface between tyre and road surface, especially those contact forces on the individual chippings. Once known, the actual interfacial stresses between the chippings and the binder could then be assessed and included in the design process.

This paper outlines the investigation which has attempted to assess the contact stresses between a tyre and road surface and interfacial stresses at chipping/binder interface and focuses upon the variations caused by different parameters. This has included the computerisation of a laboratory test pad utilising a bridged 'T' piece capable of measuring three dimensional dynamic stresses. After a number of tests the distributions of the contact stresses between tyres and road surface were derived. The effect of different sensor heights (size of chipping) and the resultant interfacial stresses are also examined.

2. THE MEASUREMENT OF CONTACT STRESSES

2.1 Computer-aided Testing System

Several Computer-Aided Testing systems for static tyres, dynamic model tyres and dynamic full-size tyres were developed.

2.1.1 Contact Stress Transducer

The contact stress between tyres and road surface consists of three components, two tangential (lateral X and longitudinal Y) and one vertical Z. A specially developed contact stress transducer incorporated three pairs of strain gauges and enabled the measurement of these three contact stress components simultaneously. A schematic drawing of the transducer is shown in Fig.1.

The basic theory of the contact stress transducer is to use strain gauges to measure the strain in the steel beam induced by the tyre/cantilever contact force, then convert the strain back to the contact stress on the top of the cantilever. The transducer consists of three main parts: (1) a steel plate - the simulated road surface; (2) a simply supported transducer beam with a cantilever bar upon which 3 pairs of strain gauges were placed; (3) a base plate which can hold transducer beams in place. The tip of the transducer beam was designed to protrude through a slot which isolated the transducer from the steel plate. The surface of the transducer was a 5 mm square sensing surface, which could be adjusted vertically to the simulated road surface level or higher when studying stresses on chippings. When the tyre moved over this transducer surface, a 5 mm wide strip distribution of the contact stresses could then be obtained. In this manner, a series of distribution strips enabled the entire contact patch to be covered.

2.1.2 Amplifier, Computer Interface and Software

To obtain the best possible resolution, the signal was amplified to ensure that the maximum voltage swing equalled the maximum input range of the A/D converter. To achieve this strain gauge amplifiers were used prior to the signal from the strain gauge being picked up by the computer.

A IBM PS/2 computer and the data acquisition board MC-MIO-16 were used for the full-size tyre testing system, a 64K BBC microcomputer and UNILAB interface were used in the model system. Although the interface could only read one input at a time, the time needed to read an input, switch to and read a second input is extremely short. This makes it possible to acquire many readings during the short time of the contact. The sensitivity of the interface could be varied according to the tyre loading and inflation pressure.

The programs for the measurement system perform mainly the following functions:

--- the calibration of the strain gauges.
--- the monitoring of the readings from the strain gauge.
--- the acquisition and storage of data in a data file.
--- the reading of a data file from the disk.
--- the plotting of graphs from the acquired data.

2.2 THE STATIC MEASUREMENT AND ANALYSIS OF THE CONTACT STRESSES

2.2.1 The Static Measurement System

A static measurement system, SF-CSMS, was set up in the laboratory. The system includes a static frame, two way hydraulic jack, contact stress transducer, amplifier, interface and computer.

12 sensing surfaces of the contact stress transducer were placed at right angles to the line of travel thus covering the complete cross-section of the tyre under test. After the readings were taken, the transducers were moved 15 mm to another measuring position. The computer and its interface board were capable of taking all 36 analogue inputs virtually simultaneously.

A HGV's tyre and a car tyre (both radial) were assessed under various loadings, tyre inflation pressures and texture depths. During the test, the tread of tyres was kept so that the contact forces on the transducers were much closer to the actual forces on the chippings, and half of the contact envelope was measured. The testing positions of the transducer surfaces are shown in Fig.2.

2.2.2 Static Contact Stresses under a HGV's Tyre

The magnitude of the vertical contact force on the transducers is highly dependent on the relative positions of the transducer surface with tyre tread. The more contact area, the greater vertical contact force generally.

Fig.3 shows typical distribution curves of static vertical contact stress which were all at the same centre strip of the tyre from the transducer 6 which was always in full contact with the tyre tread during the tests. From the figure, it was known that the longitudinal distribution of the vertical contact stress was relatively even in the middle region of the tyre. When the height of the transducer surface increased from 0 mm to 1 mm, the contact stress was approximately doubled at every position. When the height of the transducer surface increased further from 0 to 2 mm, the contact stress was approximately trebled. Similar results were obtained from the car tyre test.

Compared with the average contact stress (about 5 to 6 kgf/cm^2) from the ratio of wheel load to contact area, the maximum measured contact stress (2 mm) is almost 10 times the average contact stress. The authors believe this to be very significant in the design of surface dressings.

Meanwhile, the tests showed that the change of the tyre inflation pressure and wheel load would appear to have little influence on the highest value of the contact stress.

The magnitude of the tangential contact forces were also highly dependent on the relative position of the transducer surface to the tyre tread. Those transducers which had full contact with the tyre obtained lower tangential contact forces and those which had partial contact with the tyre tread obtained greater tangential contact forces. This is because the partially contacted transducers were pushed to the side by the tyre tread. The results showed a similar relationship in the vertical contact force, ie the height of the transducer surface had much greater influence on the contact force than tyre inflation pressure and wheel load. However, because of the static test, the magnitude of the tangential contact force was not very significant.

2.3 THE DYNAMIC MEASUREMENT AND ANALYSIS OF THE CONTACT STRESSES

2.3.1 CAT Dynamic Measurement System

The measurement of dynamic contact stresses has proved to be much more difficult due to the very short contact time between a moving tyre and road surface (only a few milli-seconds).

To investigate the dynamic contact stresses, a model CAT system WTM-CSMS and a full-size CAT system RV-CSMS were developed.

WTM-CSMS is a model Computer-Aided Testing System to measure the dynamic contact stresses between a moving model tyre and a simulated road surface in the laboratory. The system includes the use of a microcomputer, computer interface, photo-electric cell switch, stabilised power supplier, amplifiers, and the contact stress transducer in association with the moving model tyre.

The moving model tyre was from the Wheel-Tracking Machine (a standard piece of equipment used to simulate the rutting of bituminous samples by traffic under laboratory conditions). The load chosen for the tests produced an average contact stress very similar to that of a loaded lorry tyre. A wheeled-tyre in the machine moves backward and forward continuously. The moving speed of the tyre is approximately 400 mm/sec (1.4 kM/hr. at the centre). The contact length may vary from 20 mm to 70 mm for the model pneumatic tyre, thus, the contact time may vary between 60 and 180 milli-seconds.

A photo-electric cell switch was attached to the machine to enable the detection of the position of the moving tyre. The cell was linked with the computer interface and so controlled the interface according to the detected position of the moving tyre.

RV-CSMS system is designed for the measurement of dynamic contact stresses under a HGV tyre. As the first stage of the investigation, the dynamic contact stresses under a moving car tyre were measured. The car was driven in a straight line at about 10 km/h in an acceleration mode.

2.3.2 Dynamic Contact Stresses

Fig.4 shows a typical vertical contact stress strip distribution under the moving car tyre with varying heights of transducer surface. In the Figure, wheel loading and tyre inflation are constant for the three curves. Although the shapes of the distribution curves are similar, the values of the curves are very different. They show that the height of transducer surface can significantly affect the contact stress. These results are very similar to the results obtained from the static tests which showed that if an individual chipping has an Average Least Dimension of 1.0 mm producing a macro-texture of 1.0 mm, it will produce a contact force twice that induced on a chipping at zero texture depth. Similarly, if an individual chipping has an ALD of 2.0 mm the contact force on it will be approximately trebled. The model tyre measurement gave similar results.

It would appear from the results that the distribution of the vertical contact stress is relatively constant when the wheel load is greatest or the tyre inflation is at its lowest pressure and that the higher inflation has a greater effect on the contact stress than the actual wheel loading.

Fig.5 and Fig.6 show two examples of tangential contact stress distributions. The tangential contact forces produce a significant variation when the texture depth of the simulated chipping, inflation pressure of the tyre or wheel loading are changed. The most significant fact is that the two tangential contact stresses change their direction during contact between the tyre and the transducer. This was also mentioned by Lippmann and Oblizajek (1). As a result of this, the resultant dynamic tangential contact force also changes its direction during contact. In Fig.7 as an example, the dynamic tangential contact force of the moving car tyre gradually changes its direction angles through 246.4°. The height of transducer surface has a similar influence on the magnitude of the maximum tangential contact stresses, ie every millimetre increase in transducer height produces 100 percent increase in the tangential contact stress.

2.4 Summary of Measured Contact Stresses

Table.1 gives a collection of all measured maximum contact stresses from the static, dynamic and model tyre measurements. The composition of the three maximum components was actually the most unfavourable condition for the contact force on a pavement surface, and it was found that the magnitude of resultant contact force was very close to that of vertical contact force. The maximum contact stress was recorded as 99.21 kgf/cm^2 on a 2.0 mm high transducer condition.

Comparing the resultant contact forces of the dynamic and static car tyres, the dynamic contact forces are double the static contact forces. Bearing this in mind, if the lorry tyre has a similar movement to the car tyre, the dynamic resultant contact force of the lorry tyre is at least double its static value. That is, 125.28 kgf/cm^2 with a 2.0 mm high transducer surface condition. If the surface chipping is higher than 2.0 mm, and the movement of the lorry tyre generates a greater dynamic force, the surface chippings will suffer much greater contact stress. It is possible that such a contact force may crush some of the weaker chippings, especially on surface dressings with a hard substratum.

The resultant tangential contact forces in the testing condition, produced values ranging from 30 to 40 percent of the vertical contact forces. If other influential action is imparted on the chipping, such as acceleration and braking, a greater tangential contact force could be experienced.

3. ANALYSIS OF DYNAMIC CONTACT FORCES ON SURFACE CHIPPINGS

3.1 Contact between tyres and a Textured Road Surface

Research has shown that both macro- and micro-surface texture depth are necessary in order to provide adequate pavement surface skidding resistance, especially for high speed roads in wet conditions. The current recommendation for minimum texture depth in the United Kingdom is 1.5 mm for all major roads, whereas in China, a minimum value of 0.8 mm is required. The tyres of road traffic are, therefore, actually supported by pinnacles of the coarse aggregate chippings which protrude above the matrix, providing a texture depth in excess of 2 mm, and not by a smooth level plane. This means that pavement surface chippings actually bear much higher contact stresses than previously estimated by an evenly distributed standard axle load over a calculated contact area. When considering non-uniformed distribution of contact stresses and the dynamic effect of moving tyres, the under-estimated contact stresses on some surface chippings may be much greater. Unfortunately, this fact has not been considered relevant by highway engineers - the authors would suggest this may be the cause of many surface failures.

3.2 Simulation of Pavement Surface Chippings by the Contact Stress Transducer

The contact stress transducer which was developed in the present investigation was designed for two purposes. Firstly, to measure the distribution of dynamic contact stresses between moving tyres and road surface; and secondly, to simulate pavement surface chippings by the transducer surface. The top part of the transducer surface is capable of simulating a surface chipping, and with its variation in height used to simulate different texture depth of a textured pavement surface. The measured dynamic contact forces on each transducer surface, therefore, may be taken as the dynamic contact forces on the same size of a individual surface chipping. This is shown in Fig.8, three contact force components acting on the top of the transducer surface.

3.3 "Rocking Effect" of Pavement Surface Chippings

It should be noted that the resultant tangential contact force is not different force acting on different chippings, but different dynamic tangential force acting on the top of the same chipping (transducer surface) continuously over a very short contact time. This means that the surface chipping is "rocked" by the resultant dynamic tangential contact force during contact. Since traffic tends to follow the same track, some surface chippings consistently suffer the rocking effect.

This rocking effect, together with much greater vertical contact stress, causes a detrimental effect on the chippings of a textured road surface. Obviously, the rocking effect speeds up the fatigue failure of the binder between surface chippings, and it may be the main contributor to the stripping away of surface chippings, as well as the polishing of chippings and to a lesser extent the wearing away of the tyres.

The deeper the texture depth, and the more actions (steering, braking and acceleration) the vehicle, the greater is the contact force, and therefore the more serious is the rocking effect on the chippings.

4. AN ANALYSIS OF THE INTERFACIAL STRESSES BETWEEN CHIPPINGS AND THE BINDER

Perhaps the most evident effect of the dynamic contact forces on pavement surface chippings is that these may cause a break in adhesion between the chippings and binder; ie the surface chippings will be stripped away. After a series of road trials by Woodside et al it was reported that the cumulative loss of surface chippings in all observed sections sharply increased after 100 days following surface dressing construction work (2). Therefore, it is considered that the affinity between surface chippings and binder, and the ability of adhesion between surface chippings and binder to resist the interfacial stresses induced in a chippings/binder matrix by dynamic contact forces should be important design considerations. The previously mentioned "rocking effect" also induces such interfacial stresses and its consequent effect of binder fatigue, together with binder ageing characteristics, will affect the binder adhesion capabilities.

The authors believe it is necessary to quantify these interfacial stresses at the individual chipping/binder interface in order to select the correct grade of binder and thus to prevent the chippings being "plucked out", and to establish relationship between interfacial stress, contact force, binder adhesion and chipping size. This would facilitate and improve the design process of this composite material on selected sites.

4.1 Virtual Displacement of Individual Surface Chipping

One possible virtual displacement of a individual surface chipping under contact forces is shown in Fig.8. The main interfacial stresses between the individual surfacing chipping and binder is given in the figure. The contact force R_{XY} is a resultant tangential contact force from the two tangential contact stress components, and F_Z is the vertical contact force. The dotted lines in the figure represent the possible virtual displacement of the surface chipping along the direction of resultant tangential contact force. Obviously, point D is the bearing point; point E and C will experience a compression force, and the greatest tensile force will occur at the position B and bottom C.

According to the above, possible failures will be that the binder at point E and C will be crushed and the bond at point B will be broken between the binder and the chipping thus causing the chipping to be plucked out.

4.2 Interfacial Stresses Between Individual Chippings and the Binder

If the compression forces which possibly occur at point C (due to the deformation of the binder) and other possible forces induced by the displacement of the bearing point are neglected and assuming that the distribution of shear force on both front and back side of the chipping and the distributions of the resisting forces (tension and compression) from the binder are all triangular (the greater displacement, the greater interfacial stress), then the relationship between contact force and chipping/binder interfacial stress can be established by the following analysis.

Considering this unfavourable balance of the bending moment about the bearing point D, the following relationship exists:

$$R_{XY}\,(L+L_1) = F_t\,2L_1/3 + F_c\,2L_1/3 + F_{bt}\,2a/3 + 2F_s\,2L_1/3 + F_Z\,a/2 \quad \text{.........(Eq.1)}$$

Where,

F_t ---- the side resultant resisting tensile force,

F_c ---- the resultant compressive force,

F_{bt} ---- the bottom resultant resisting tensile force,

F_s ---- the shear force on both front and back side.

The above forces all act through a point which is one-third of the length of the side from the maximum stress. R_{XY} and F_Z are correspondingly the resultant tangential and vertical contact forces, and a is the width of the surface chipping.

It is assumed that the capacity of the binder to resist tensile stress is equal to that which can resist shear stress. (When displacement between the chipping and the binder is too large in the working condition, the binder ceases to function.)

If the capacity of the binder to resist tensile stress is lower than that of its resistance to compressive crushing, it then can be assumed that the maximum value of distributed resisting tensile stress and shear stress will first reach their limit f_t. Then, (Eq.1) can be expressed as (Eq.2):

$R_{XY}*(L+L_1) =$ $F_c*2L_1/3 + 2L_1/3*L_1/2af_t + 2a/3*a/2*af_t + 2*a*L_1/2*f_t*2L_1/3 + F_Z a/2$ ....(Eq.2)

Thus, the resisting compressive force F_c of such a condition can be obtained:

$$F_c=\frac{3R_{XY}(L+L_1)-af_tL_1^2-a^3f_t-2af_tL_1^2-\frac{3}{2}aF_Z}{2L_1}\quad ..(Eq.3)$$

As the resisting compressive force F_c is assumed to have a triangular distribution, the following equation can be established also:

$$f_{cE}=\frac{3R_{XY}(L+L_1)-\frac{3}{2}aF_Z-af_tL_1^2-a^3f_t-2af_tL_1^2}{aL_1^2}\quad ..(Eq.4)$$

Where, f_{cE} ---- the maximum value of the distributed resisting compressive stress at the point E, see Fig.8.

If the value f_{cE} is greater than the critical value f_c which the binder can resist, the displacement of the chipping will continue, and the interfacial stress will increase until the chipping is plucked out.

On the other hand, if the capacity of the binder to resist compressive crushing is lower than that its resistance to tensile stress, it then can be assumed that the maximum value of distributed resisting compressive stress will first reach the limit f_c. Then, by the same idea, equation (Eq.3) can be expressed as equation (Eq.5):

$$f_{tB}=\frac{3R_{XY}(L+L_1)-\frac{3}{2}aF_Z-af_cL_1^2}{aL_1^2+a^3+2aL_1^2}\quad ....(Eq.5)$$

Where, f_{tB} is the maximum value of the distributed resisting tensile stress at the point B, see Fig.8.

If the value f_{tB} is greater than the critical value f_t which the binder can resist then the displacement of the chipping will continue and the interfacial stress will increase until eventually the chipping is plucked out.

In practice, the Average Least Dimension of surface chippings can be used for L + L_1, the texture depth for L, and the nominal size of surface aggregate can be used for a. R_{XY} and F_Z are the maximum values of the actual measured contact force. All the units in the above equations are in kgf. and centimetre units. The f_t value is not easy to obtain, but according to the Limpet Test(3), the f_t value is approximately 2 - 4 kgf/cm^2.

Using a short computer program for the calculation of (Eq.4) and (Eq.5) is easy. The stress f_{cE} (or f_{tB}) can be calculated by every millimetre, from zero texture depth (whole chipping below the binder surface) to that the texture depth equal to surface chipping size (whole chipping exposed outside the binder). It should be noticed that R_{XY} and F_Z are not independent constants, and they will increase with the surface texture depth L. The maximum measured contact forces R_{XY} and F_Z at the zero texture depth are used at the beginning of the calculation, and then there is 100 percent increase of contact forces for every millimetre increase of the surface texture depth. Various chipping sizes, texture depths, contact forces and binder properties can be input from the keyboard.

According to the calculation, the magnitude of maximum distributed resisting compressive stress to the surrounding binder is highly dependent on the performance of the vertical contact force F_Z. The tangential contact force R_{XY} plucks out the surface chipping, while the vertical contact force F_Z holds the surface chipping. If the surface chippings are cubicle with the ALD vertical, straight moving traffic will not be able to pluck out the chippings in normal surface texture depth. However, if the tangential contact force increase in proportion to that in Table.1 (such as in braking, acceleration and steering), or if the chipping surface is not level and the vertical contact force F_Z acts on the bearing point line (this may be caused by surface chipping not with the ALD vertical), the compressive force on the surrounding binder may be very large. This may exceed 10 kgf/cm^2 with a 2.0 mm texture depth and this is beyond the limit of a standard bitumen binder. Meanwhile, as assumed earlier, the resisting tensile force also reaches its limiting value. If these occur, surface chippings will be plucked out, especially those already weakened by chipping surface dust, temperature change and poor binder quality. Once surface chippings are plucked out, water will easier affect a pavement and this may lead to local failure.

Equation 5 actually provides a rational relationship between external contact force and chipping size, texture depth and binder properties, that is the relationship between macro-element (contact force) and micro-element (surface texture) of a tyre/pavement interface characteristics. It makes it possible to select a proper surface chipping size, shape, texture depth and binder properties according to the actual requirement of the traffic.

5. DISCUSSIONS

Based on the findings of this investigation and calculations from the model, the authors would suggest that individual chippings in a high textured pavement surface may not be adequately retained by the binder alone, especially for surface chippings located within high contact stress sections of a highway pavement, such as at intersections and on steep gradients. This being the case, then the design process of the pavement composite material must ensure that the surfacing chippings are interlocked with each other so that the formed mosaic pattern can share the resisting compressive force on the binder. It is also suggested that greater care must be taken in the selection of a binder and its proportion of the resulting composite material. Consequently, special treatments may be necessary for high stress sections of the highway.

However, there still remains some unsolved problems with the mechanical model. On actual pavement surfaces, the isolated chippings do not protrude from the flush level of the original road surface, but many chippings protrude side by side to a similar level to form the pavement surface texture. Thus, actual contact stresses on individual surface chipping may be lower than the contact stresses measured by the contact stress transducer, as the load is being spread over a number of chippings. The difference between the two values needs to be analysed. Consequently, the difference of the surface roughness between chippings and transducer surface may also affect the measured values of tangential contact stress.

6. CONCLUSIONS

The CAT systems for measureing both static and dynamic contact stresses have been developed. The results obtained have shown that the contact stresses between a tyre and textured road surface are much higher than that commonly used (average contact stress figures) in pavement design. The contact stresses on individual surface chipping have been obtained and a "rocking effect" was found existing for surface chippings. Initial mathematical relationships have been established which creates a direct connection between external contact force (macro-element of tyre/road interaction system) and chipping size, shape, texture depth and binder properties (micro-element). These relationships may be of benefit in the improvement of the design process of the complex composite materials of a pavement. The relationships may also provide the connection between the microstructure of the road surface and anti-skidding pavement design. It may also enable the highway designer to forecast where "plucking" is likely to occur in the high contact stress sections and suggest what special treatments should be recommended in these circumstances.

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TABLE.1 Measured Maximum Contact Stress on Pavement Surface Chippings

(kgf/cm^2)

item		Z	Y	X	resultant Z, Y, X
static lorry tyre	0.0 mm	20.24	4.16	4.40	21.13
	1.0 mm	37.20	7.56	9.20	39.06
	2.0 mm	60.00	11.68	13.68	62.64
static car tyre	0.0 mm	13.00	2.44	3.04	13.57
	1.0 mm	25.00	6.00	8.16	26.97
	2.0 mm	38.40	8.40	11.24	40.88
dynamic car tyre	0.0 mm	21.92	-8.00	7.36	24.47
	1.0 mm	49.92	-14.8	10.04	53.03
	2.0 mm	75.04	22.48	10.24	79.00
PSV tyre equivalent 50psi, 30kgf	0.0 mm	13.91	2.38	4.42+	19.54
	1.0 mm	31.03	3.60	5.72+	31.76
	2.0 mm	53.22	5.22	12.59	54.94
solid tyre equivalent 30kgf load	0.0 mm	25.76	2.24	1.64	25.91
	1.0 mm	60.80	3.68	3.80	61.03
	2.0 mm	98.68	8.68	5.48	99.21

Note: * PSV pneumatic model tyre, average contact stress is about 4.60 kgf/cm^2 when the tyre inflation is 50 psi and load 30 kgf, slightly lower than lorry condition.
* WTM solid tyre, average contact stress is about 4.8 kgf/cm^2 when wheel load is 30 kgf, slightly lower than lorry condition.

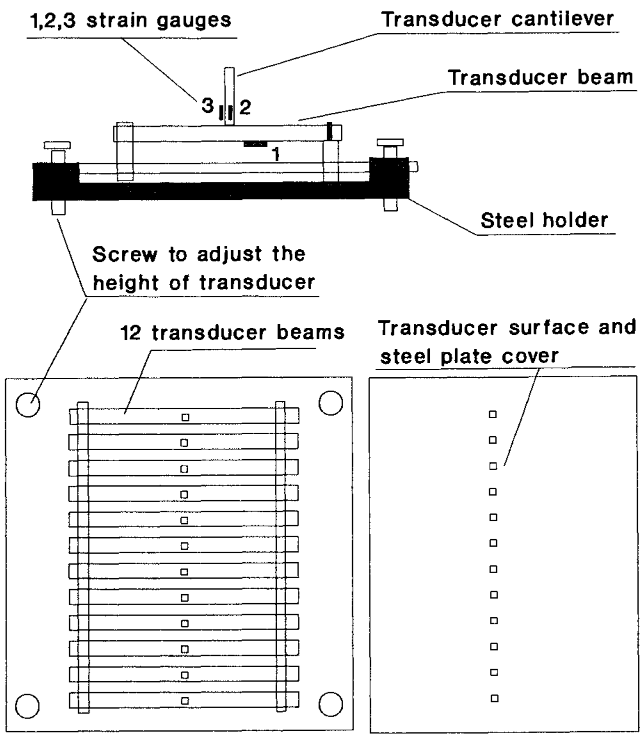

Fig.1 Contact Stress Transducer Schematic

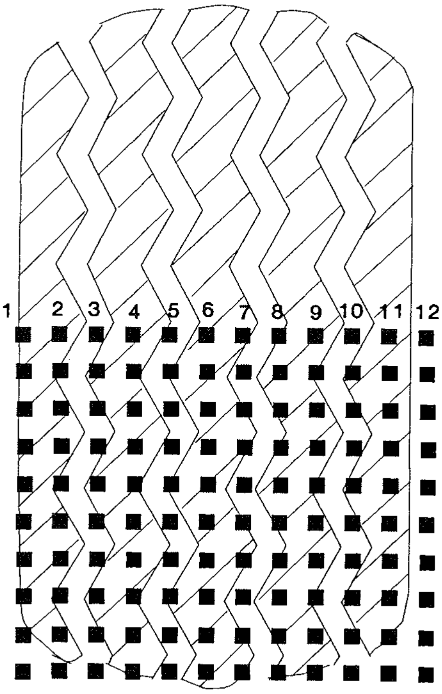

Fig.2 Locations of Transducer Surfaces under A Lorry Tyre

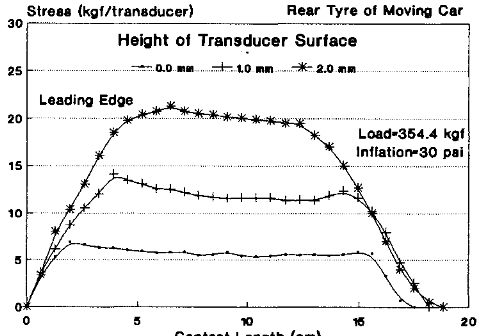

Fig.4 Vertical Contact Stress for the Car Tyre

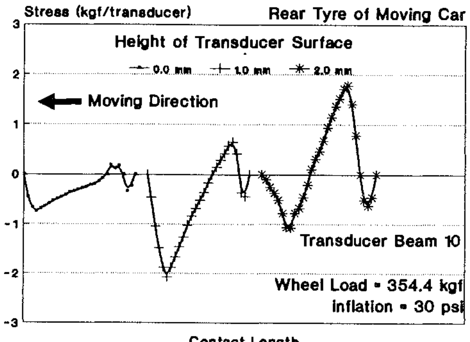

Fig.5 Longitudinal Contact Stress with Transducer Heights

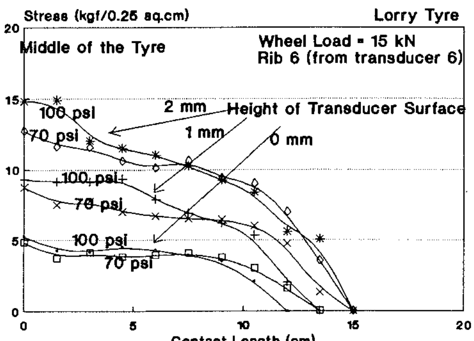

Fig.3 Vertical Contact Stress for Lorry Tyre

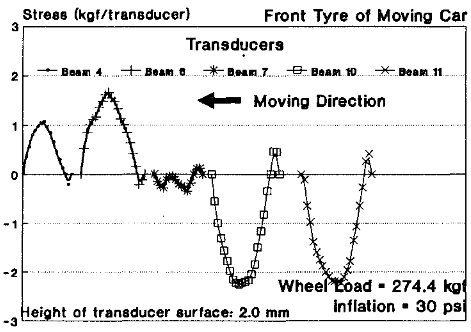

Fig.6 Lateral Contact Stress with Transducer Locations

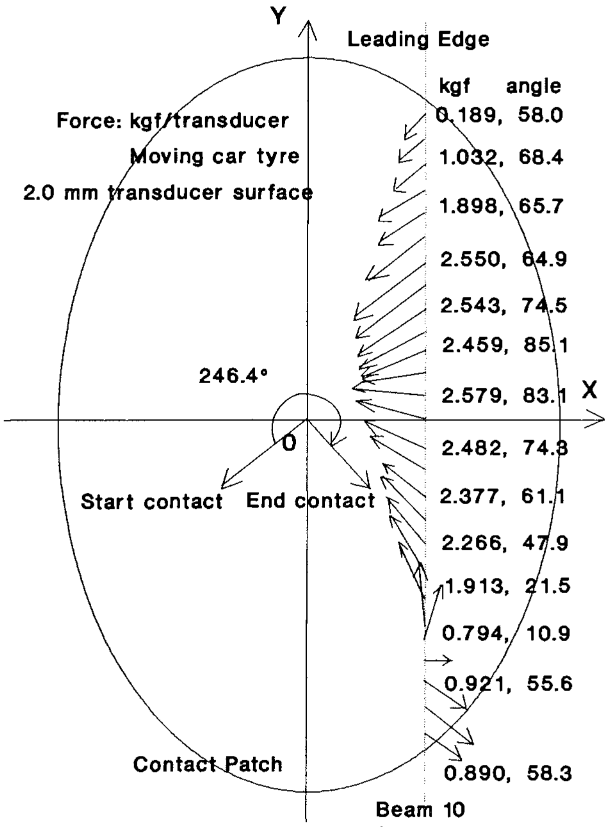

Fig.7 Resultant Tangential Contact Force Values and Direction on Individual Point

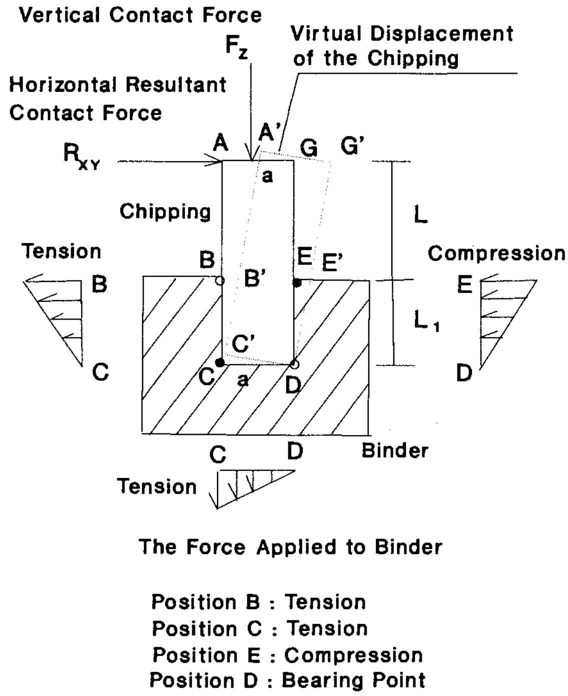

Fig.8 Analysis of Interface Stresses Between Surface Chipping and Binder